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# **AN ASSESSMENT of THE RELATIONSHIP BETWEEN AIR MASS FREQUENCY and EXTREME DROUGHT in the MIDWEST UNITED STATES**

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## **ABSTRACT**

The Midwest of the United States is a region extensively utilized for agriculture and livestock production despite great susceptibility to widespread and persistent drought. While the location and duration of droughts are related to dynamic meteorological factors, pinpointing when and where a drought will commence, how long it will persist, and when the drought will end, remains a challenge. This investigation examines significant Midwest drought events from a synoptic meteorological perspective through an assessment of air mass frequency over the past decade. A synoptic approach is useful since air masses characteristically describe multiple weather and climate parameters at the same time across wide areas. The daily air mass conditions in the Spatial Synoptic Classification that are dominant during extreme droughts are examined across the

region and compared to “normal” periods without substantial or extensive drought. Extreme episodes are established with new criteria expanded from United States Drought Monitor information, normal average decadal and seasonal baselines are calculated, and the air mass frequency departures from these periods are examined for statistical and practical significance. Results indicate that the Dry Polar, Dry Tropical and Moist Tropical air masses exhibit important and statistically significant changes in frequency during drought. Tendencies for substantial increases in warm and dry types, regardless of season, and moist air mass declines are detected. The exact air masses with significant changes are unique for different sub-regions, particularly in the northwest and south. These patterns are consistent with changing upper-air flows such as southerly, meridional flow to more southwesterly, zonal flow.

## **INTRODUCTION**

Widespread and persistent drought events occur on all continents of the world. The Southern Plains of the United States has experienced a substantial drought during 2011. A majority of range and pastures across the region were classified in “very poor” condition. Current estimates of the direct economic impact to crops top \$10 billion, though this number is expected to rise as the drought has persisted into 2012 (NOAA, 2012). The severe 2010, drought in the Amazon River Basin follows one in 2005, that has been deemed a "one in a century" event (Lewis, *et al.*, 2011). Concerns about these recent droughts have

centered around the ability of the forest to absorb carbon dioxide when trees are sparse, stressed and even on fire. In the United States, drought is the most costly variety of natural disaster accounting for, "\$144 billion of the estimated \$349 billion total cost of all

weather-related disasters" (Mishra and Singh, 2010). Table 1 notes the country's top five weather related disasters since 1930, where the second and third most expensive are droughts (adjusted to 2007 United States dollars).

<b>Year</b>	<b>Event/ Description</b>	<b>Cost</b>	<b>Mortality</b>
<b>2005</b>	Hurricane Katrina	133.8 Billion	1,833
<b>1988</b>	Drought, Heatwave (El Niño)	71.2 Billion	5,000 – 1,000*
<b>1980</b>	Drought, Heatwave (El Niño)	55.4 Billion	10,000*
<b>1992</b>	Hurricane Andrew	40 Billion*	61
<b>1993</b>	Midwest Flooding (Missouri & Mississippi Rivers)	30.2 Billion*	48

**Table 1.** Top five costliest U.S. weather phenomena (reported as adjusted to 2007 U.S. dollars) since 1930 and reported human mortalities (NCDC 2011). \* indicates an approximate value

Efforts to understand and minimize the impact of droughts have been focused on the country's highly populated regions such as the Northeast and Pacific Northwest (Klugman, 1978). Nevertheless, areas with less population density, such as the Midwest, are more commonly affected by drought (Diaz, 1983). Here, droughts can last for several weeks to months, years or longer. Tree ring data from Nebraska indicate that some droughts have persisted in the central United States for up to four decades (Diaz, 1983). Droughts in this region can quickly impact the productivity of the entire country since 40% of the Upper Midwest is used for agriculture and livestock (RESAC, 2002). The 2007, census

report indicates that there are 639,208 farms across the region with operations that support over \$82 million in revenue with over \$62 million in production costs (Table 2). The region is a leading producer and exporter of corn, soybeans, dairy, sugar beets, apples, turkeys, pigs, cattle, cranberries and wild rice. These agricultural areas are highly susceptible to drought and when yields are affected there are longstanding negative economic impacts that can include job and business/industry losses, rising produce prices and modifications to the physical landscape that lead to soil erosion, runoff and wind damage.

<b>State</b>	<b>Number of Farms</b>	<b>Revenue</b>	<b>Costs</b>
<b>IL</b>	76,860	13,329,107	9,045,080
<b>IN</b>	60,938	8,271,291	6,280,596
<b>IA</b>	92,856	20,418,096	15,443,759
<b>KY</b>	85,260	4,824,561	3,930,240
<b>MI</b>	56,014	5,753,219	4,786,767
<b>MN</b>	80,992	13,180,466	10,320,405
<b>MO</b>	107,825	7,512,926	6,135,205
<b>WI</b>	78,463	8,967,358	6,748,715
<b>Total</b>	<b>639,208</b>	<b>82,257,024</b>	<b>62,690,767</b>

**Table 2.** Midwest region agricultural statistics based on the 2007 U.S. Census (USDA 2009).

One setback to examining droughts in the United States, regardless of region, lies in the fact that there is no one scientific definition of a "drought". This is due in part to their complex manifestation across an area and widespread effects (Heim, 2002). Without a working definition, episode classifications are inevitably variable and inconsistent across the discipline or, at least, contain uncertainty which can hinder drought forecasting abilities (Chagnon, 2002). According to the American Meteorological Society (AMS), drought is defined as, "an extended interval of abnormally dry weather sufficiently prolonged for the lack of water to cause a serious hydrologic imbalance" (Geer, 1996). Other definitions are presented in the following section.

Given the severity and complexity of the problems that drought can bring about in the Midwest, it is crucial to obtain more information on the spatial and temporal patterns of drought in this region. It is especially important to be able to provide adequate warning to farmers, distributors, manufacturers and consumers on the timing

of drought persistence. This should include: 1) where and when a drought will initiate, 2) how long the drought will persist, and 3) when the drought will end. Local populations will generally benefit from this information as it may provide necessary time for preparations and adaptations. For example, knowledge of drought patterns will allow consumers to anticipate market price fluctuations as distributors can prepare to organize buying and selling operations according to product availability.

To this end, drought classification systems have become integral to decision makers that require information about drought forecasting and management. Within the atmospheric sciences, the Palmer Drought Severity Index (PDSI) has seen extensive use in classifying the intensity and persistence of droughts over the past several decades (Palmer, 1965). The PDSI is a numerical meteorological index that uses temperature and precipitation data to categorize droughts which can then be spatially interpolated across a region. Output maps from the PDSI are made operationally available through the National Oceanic and

Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) (NCDCa, 2011).

Another avenue for obtaining drought classifications, the United States Drought Monitor (USDM), is operated by a suite of government agencies including NCDC, the National Drought Mitigation Center (NDMC), United States Department of Agriculture (USDA) and NOAA Climate Prediction Center (CPC) (Svoboda, *et al.*, 2002). This system incorporates several drought indices into a holistic classification scheme while additionally ranking droughts based on their societal impacts, such as when a drought is presently affecting agricultural areas or local watersheds (Svoboda, *et al.*, 2002). The classification scheme entails rankings from D0 to D4 (D0 = abnormally dry conditions, D1 = moderate drought conditions, D2 = severe drought, D3 = extreme drought and D4 = exceptional drought conditions). The USDM data are made readily available to the public in tabular form and as spatially interpolated maps via a website (USDM, 2011).

From an atmospheric science standpoint, it is well understood that the location and duration of drought are related to dynamic synoptic meteorological factors like persistent, anomalous departures from normal atmospheric circulation patterns. Anticyclone blocking patterns are an example of this and occur regularly over the Southeast to produce periods of summertime drought. Droughts are often associated with lengthy intervals of anomalously low precipitation though they can also occur when storm systems are active over a region but precipitation totals are too low to sustain

normal regional productivity. An example of this is when a region receives rainfall but it is an insufficient amount for crops to grow or flourish. Alternatively, droughts can occur when total rainfall is anomalously low compared to seasonal averages (McNab and Karl, 1989). Droughts are also known to occur during extended periods of low cloud fraction (clear sky) days (Freedman, *et al.*, 2001). There is also some indication that droughts occur when periods of above-average surface temperatures are observed though the relationship between drought and temperature is complex and not fully understood (Kalkstein, *et al.*, 1990).

Given that droughts are related to many anomalous meteorological conditions rather than one persistent weather parameter, exploring these relationships is worthwhile to better understand and forecast droughts in regions such as the Midwest. One way this can be achieved is with an assessment of the dominant air mass conditions present during drought episodes. This information is useful to obtain since air masses characteristically describe multiple weather and climate parameters at a given time across wide areas rather than single point-by-point meteorological readings (AMS, 2011). Sheridan (2002) redeveloped a Spatial Synoptic Classification (SSC) scheme that uses automated and manual processes to classify weather types that is considered here to be a highly valuable tool for drought assessment and prediction. Though source regions are not considered, the SSC provides a mechanism for defining air masses by incorporating a location's surface temperature, dew point, wind, pressure and

cloud cover data measured 4-times daily to categorize seven air masses.

The primary goal of this research is to approach the issue of extreme Midwest drought on a synoptic meteorological level through an assessment of air mass frequency to see if a relationship exists between any one air mass type and the timing of extreme drought. More specifically, air mass frequency differences from times of “normal” conditions will be examined for statistical and practical significance during all intense drought events over the past decade. To ensure that only the driest days of the past decade are examined, “extreme” droughts are defined using new criteria from available USDM classifications for all Midwestern states that exhibit similar drought tendencies. Frequency departures will be evaluated against period of record and seasonal average conditions to test whether or not different air masses are related to intense droughts at different times of year. It is hypothesized that, while the entire decade may be drier than average in the Midwest, during extreme droughts the region experiences even more dry air masses and even fewer moist air masses than average. This investigation should ultimately help determine whether or not air masses are a useful resource for predicting extreme drought in the Midwest.

## **BACKGROUND & LITERATURE REVIEW**

Just as the synoptic meteorology of a region can initiate drought, a drought can have important implications for the meteorological conditions that prevail long

after a drought is underway. There are four common ways to define droughts that occur over a period of time: 1) meteorological drought, 2) hydrological drought, 3) agricultural drought and 4) socio-economic drought. The length of time required for these conditions is debatable among the scientific community and, subsequently, there are no set ‘duration’ criteria in the definition of drought. A *meteorological* drought occurs when an area has a lack of precipitation over a period of time. A *hydrological* drought relates to a period of time with insufficient water resources for a particular water resource management system. An *agricultural* drought refers to an extended period of time with declining soil moisture resulting in crop failure. Finally, a *socio-economic* drought is defined as a time with general failures in water systems to meet water demands (Mishra and Singh, 2010). These definitions will be considered throughout this investigation as severe and extreme droughts (defined by the USDM) are examined synoptically in this research.

## **Synoptic Climatology of the Midwest**

The climate of the Midwest exhibits large spatial variability patterns within its geographical confines and is one of the most diverse in the continental United States. The central interior location contributes to the great extremes recorded in the Midwest (from very high summer temperatures to very low winter temperatures) (Fig. 1) (ESRL, 2011). As an example, the normal January average temperature at Duluth, MN is -13.1°C while the normal average July temperature is 18.6°C (NCDCb, 2008). In

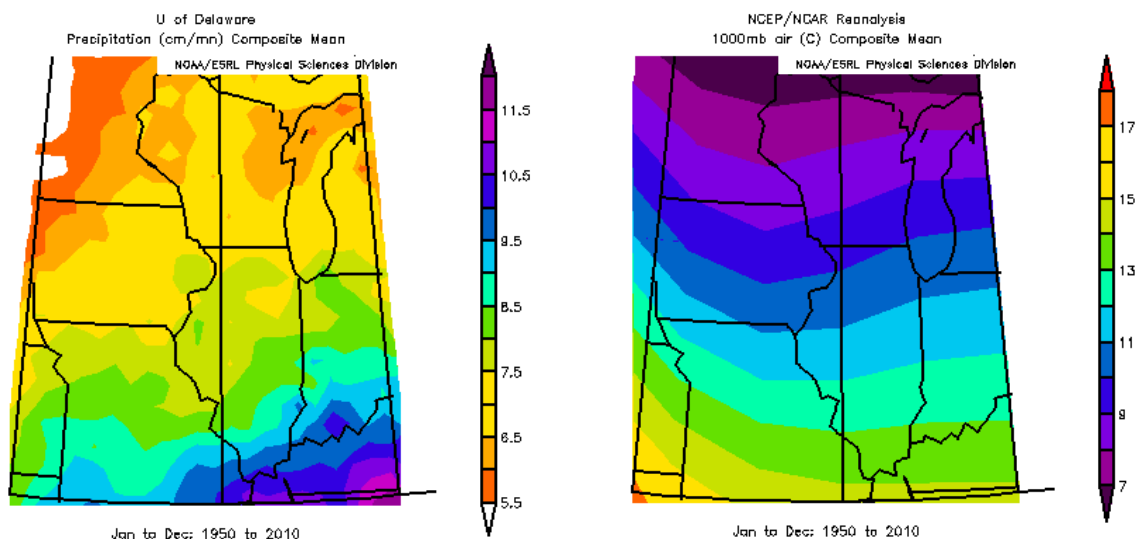


the south, at Paducah, KY, 0.5°C and 25.7°C are the normal January and July average temperatures, respectively.

Climatic differences throughout the region reflect gradual changes in both latitude and longitude. With latitude, elevation gradually increases as temperature decreases from the southern reaches to the Canadian border. These thermal changes correspond to shorter growing seasons at the highest regional latitudes. The vegetative cover across the region is also related to temperature changes. Temperature gradients directed southward lend to less coniferous forest cover and increased mixed varieties, including many deciduous species (GUSA, 2004).

Longitudinal differences are predominantly based on precipitation variability with greater rainfall totals

measured at eastern and southern locations. Annual rainfall across the region (with most received during the productive April – November agriculture months) exceeds 76.2 centimeters. The peak growing season in the north is approximately four months long but extends to over five months in the southern reaches with greater precipitation totals (fig. 1) (ESRL, 2011). The moisture sources for much of the regional precipitation are the nearby Great Lakes and more distant Gulf of Mexico advections. Warm Gulf air is a primary source of moisture that gets directed toward the region during the summer rainy period. Arctic air in the winter, however, brings cold, dry air to the region. Snowfall originates when mid latitude systems moving east from the Rockies collide with Arctic air, especially at locations nearest the lakes (GUSA, 2004).



**Figure 1.** 1950 – 2010 annual mean precipitation (left) and air temperature (right) at 1000mb (created at ESRL 2011).

## Drought in the Midwest

The most prominent drought to impact the Midwest region corresponds to the country's most significant of the past century: the Great Dust Bowl of the 1930s. Over a decade of severe drought, amplified by unsustainable farming practices, led to blowing winds and extensive topsoil erosion (White, *et al.*, 2008). Nearly 75% of the topsoil on the Great Plains was blown away by the 1940s. As a result, the value of farmland decreased, causing losses of almost \$2 billion and 8.5% population declines (NBER, 2009).

Another historical Midwest drought, the Drought of 1980, initiated with a ridge that developed over the Plains states in late spring. As the ridge strengthened anomalously high temperatures were recorded across the region, culminating in heat wave and drought. Millions of crop acreage were destroyed by drought conditions and thousands of livestock perished, costing over \$20 billion in agriculture industry losses (NCDC, 2011). The corresponding heat wave was attributed to nearly 1,300 fatalities (Karl and Quayle, 1981).

Another ridge-building meteorological event initiated the Drought of 1988 over the Midwest, persisting through the spring and summer seasons. Total precipitation for the Corn Belt growing season declined to 43% of seasonal normals and corn yields were 64% less than the annual average in Illinois (Lamb, 1992). Similar effects across the region resulted in \$40 billion in agricultural damages and between 5 – 10,000 heat-related mortalities

are attributed to the 1988 drought (NCDC, 2011).

Some of the worst droughts in the region lasted multiple years and even decades (referred to as mega-droughts). Societies impacted by these longer duration drought intervals include the Mississippian tribes that dotted the country's heartland in the few centuries before the voyage of Columbus. Tree-ring climate reconstructions reveal that many tribes disappeared or abandoned entire regions due to below average moisture conditions that persisted for almost a century. In some cases, severe droughts occurred for decades intermittently during a single mega-drought interval (Cook, *et al.*, 2007).

Drought causes significant socio-economic hardship; however, false alarm can be equally devastating. In March of 2000, NOAA issued a long-range forecast for the Midwest stating that a drought would persist and strengthen through the spring and last into the summer. Many farmers responded preemptively to cut their losses with crop production shifts, crop insurance purchases, and changes to their grain market choices. This significant drought event never materialized as heavy rains impacted the region from May through July. However, farmers counted losses of \$1.1 billion in the Midwest due to their precautionary measures. False alarm drought forecasts can be as disastrous as actual drought events (Changnon, 2002).



## Environmental & Economic Impacts of Drought

Drought impacts to crops are highly variable between species and their growing conditions. Increasing surface temperatures and heat stress in fields such as corn, wheat, rice and cotton can lead to faster growth rates and, therefore, less time for seeds to reach maturity (USGCRP, 2011). Higher temperatures can also result in increased soil evaporation rates which can further deplete agriculture productivity and necessary cooling processes by reducing the available plant and ground moisture. In times of drought, this can be confounded by less total precipitation and decreased precipitation rates (EPA, 2010). Agriculture in other regions of the world, such as grain growth within the Fertile Crescent, has also been examined for sensitivity to inter-annual precipitation variability. Zaitchik *et al.* (2007) identified larger vegetation in the southern confines of the region, especially during anomalously wet years. These grain crops disappeared entirely during a drought year. Livestock and the growth of food for fodder can also suffer from the effects of drought. In Balochistan, Pakistan this was documented in a study done by Shafiq (2006) in which the amount of available fodder and water declined. This resulted in fewer animals and fewer healthy animals.

There are some measures that can be taken to help alleviate agricultural production losses during times of anomalous atmospheric variability patterns. Farmers can alter planting dates or the crop varieties planted, purchase crop insurance, and invest in stress tolerant seeds (Changnon, 2002;

USGCRP, 2011). In Mexico, farming strategies and practices have been implemented for adapting to arid conditions which has enabled agriculture to expand into high risk drought locations. This is considered imperative to prevent national famines during drought while modern technologies appear to have already assisted in reducing the extent of famine (Liverman, 1990).

Nakagawa *et al.* (2000) found that severe droughts can additionally pose problems for climate regions, like that of the Midwest U.S., that are generally humid. This often includes droughts associated with El Niño episodes along humid coasts where forest dynamics may be affected. Generally, the first visible sign of drought impacts on forest trees is leaf wilting though impacts can be far more severe for some regional species. Droughts can induce stomatal closures in leaves to prevent excess loss of water. The lack of gas exchange, specifically carbon dioxide, to the atmosphere is a damaging consequence that can stunt growth and decrease annual ring widths. It is for this reason that tree rings are widely used as climate and meteorology proxies for environmental moisture flux (Coder, 1999). Lag effects can be detected for some impacts after the drought has ended. For example, new stem segments and leaf buds can be greatly reduced and adversely affect general tree health. This can produce vulnerabilities to pest infestation which can be lethal for many tree species (Coder, 1999).

Many non-agricultural economic sectors are also profoundly impacted by drought. For example, tourism and

recreational industries have increased admission prices to compensate for equipment and sustainability practices that have been invested to save water resources during drought. Rising prices can pose secondary impacts, in deterring visitors and the profit earned by these facilities. Examples include restaurants and hotels that must carefully evaluate their water consumption and adjust prices accordingly (SDSU, 2004).

### **Drought Forecasting**

In the United States, the PDSI and USDM rankings are just two of many methods used to identify, quantify and categorize drought severity and many private, academic and government resources are addressing this meteorological hazard in the form of drought indices. The inputs used to develop these systems generally differ, as do the advantages and disadvantages of using any given index. Collectively, they represent the international importance placed on obtaining as much information as possible on droughts. The National Integrated Drought Information System (NIDIS) in collaboration with NOAA and the Western Governors' Association have new initiatives in place to develop a drought early-warning system (Schubert, *et al.*, 2007). This system combines meteorological variables with socio-economic considerations to prevent incidents similar to the "failed" Midwestern drought forecasts of 2000 (Changnon, 2002). Internationally, similar drought developments are in progress. In Mexico, Artificial Neural Networks (ANN) have been deployed with

the intention of utilizing a mathematical gridded network to detect the onset of drought conditions in the Conchos River Basin (Kim and Valdes, 2003). Smakhtin and Hughes (2007) have also introduced an automated methodology for displaying and analyzing multiple drought indices at once. This program, referred to as Spatial and Time Series Information Modeling, was developed in South Africa and is currently in use throughout several African nations.

The PDSI is widely accepted as a useful tool for describing and mapping droughts that occur over large time scales. Recently the PDSI was modified to account for deviations in its Hydrological and Meteorological Index components that render it insufficient at detailing droughts at temporally small scales, such as months and weeks (Weber and Nkemdirim, 1998). Information at these scales is necessary for operational decision-support systems, especially as related to agricultural practices. Other indices have also been developed to better describe and address limitations in our predictions of drought in the United States. Wells et al. (2004) devised a Self-Calculating Palmer Drought Severity Index (SC-PDSI) to account for spatial cohesion issues attributed to precipitation variability. In addition, Rhee and Carbone (2007) developed a Palmer Modified Drought Index (PMDI) to be used in both historical archiving and near real-time drought assessments.

The Forecast Precipitation Index (FPI) has also been used by farmers to anticipate drought conditions since FPI forecasts are issued as precipitation departures from climate normals. Given the

success of the FPI in assisting water managers in the Southeastern United States and the farmers that voluntarily suspend irrigation activities under Georgia's Flint River Drought Protection Act, the FPI is now used in decision-making practices and government policies (Steinemann, 2006). In Italy a similar means of assessing regional precipitation trends, the Standardized Precipitation Index (SPI), is used as an international Mediterranean drought warning system (Cancelliere, *et al.*, 2006).

In addition to station-based indices that use precipitation and temperature data from point locations to determine drought conditions over an area some indices, such as the Vegetation Condition Index (VCI) and the Normalized Difference Vegetation Index (NDVI), use satellite data and imagery to identify drought conditions. These indices are considered beneficial due to the increased areal coverage of satellites that extends over longer temporal periods than is available at weather stations. Nevertheless, Quiring and Ganesh (2009) researched drought events in Texas and indicate that VCI estimates of drought depict very weak correlations to the station-based indices even given the wide range in intra-state correlations. Their results support the PDSI as a better index at capturing short-term drought or flooding conditions while VCI is more representative of long-range drought conditions given the high dependency on regional vegetation coverage and type.

In addition to meteorological drought indices, hydrologic and agricultural drought indices (such as the Standard Runoff Index) attempt to define drought through the use of

river and stream runoff conditions and records of soil moisture anomalies (Dubrovsky, *et al.*, 2009). Teleconnection pattern indices are not currently used as a parameter within the aforementioned drought forecasting tools though the relationship between these climate oscillations and drought is well documented. For example, Di Mauro *et al.* (2005) identified a correlation between the North Atlantic Oscillation (NAO) and severe drought episodes in the Mediterranean Basin. Schoennagel *et al.* (2005) also found a statistical relationship between drought conditions prone to increased fire dangers and the El Niño/ Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

With so many techniques for early drought identification there are still setbacks to improving drought index forecasting abilities. Namais (1955) summarized the complexity of modeling drought initiation for a wide array of Earth surface covers (grasslands to forests to glaciers) and elevations (valleys to plains to mountaintops) given incoming shortwave radiation fluxes in response to latent heat exchanges within the atmosphere (from condensation to evaporation and precipitation variability). Over 50 years later these concerns have yet to be fully resolved in any one drought index and numerical model. In addition, Dubrovsky *et al.* (2009) claim that while drought indices such as the PDSI and SPI are good proxies for determining drought conditions with modern observations, these indices are inadequate for representing droughts if future climate change occurs. To this end, a set of relative

drought indices (rPDSI and rSPI) have been introduced so that the indices can account for variability in global climate. Kingse (2008) noted that users should still be aware of certain deficiencies of the PDSI and rPDSI, such as the inability to account for frozen precipitation and snow melt in the index calculations.

### **Air Mass Classification**

The Spatial Synoptic Classification (SSC) designates an air mass type to every day of the calendar year for nearly the last 60 years at over 400 United States locations. A single air mass type describes all of the locations that have similar thermal and moisture atmospheric conditions at a given point in time. At each available station, it is the surface weather present, in concert with what occurs at nearby locations (achieved with weighting procedures for nearby stations), that determines a day's air mass type category. There are six main types and one transitional (TR) type of air mass. All air masses, including TR, can be experienced at any time of year. The major air mass categories are dry polar (DP), dry moderate (DM), dry tropical (DT), moist polar (MP), moist moderate (MM), and moist tropical (MT). These air mass types are similar to the Bergeron classification scheme (*i.e.*, mT, cT, mP, mT, cA) developed in 1930 (Sheridan, 2002).

A considerable advantage of the SSC classification is that it does not depend upon a geographical source region. This is important since air masses can be classified without uncertainty when situated far from the “corners” of the contiguous United

States, well into the interior continental reaches. Therefore, surface meteorological attributes alone control the categorization of the overlying air present in a given air mass within the SSC scheme. Another benefit to using the SSC over the Bergeron classification is that the procedure for selecting days into a category is derived from a combination of manual and automated input methods which allow human expertise of weather conditions to coincide with the precision of computer algorithm processing (Sheridan, 2002). Finally, this air mass index can account for the common occurrence of air mass modifications as well as the separation of the most extreme days (thermally, and with respect to moisture) of an air mass into a new type (designated with a +/- system). This has proven quite valuable, and has even saved lives during summer heat waves, for research that requires the evaluation of extreme air mass days.

The DP air mass type is associated with the Bergeron cP, as it includes days with air that is very cold and very dry. The DT type has the hottest and driest air, which is similar to the cT type from the Bergeron scheme. The DM air mass is also dry but with more moderate temperatures than DP, something generally experienced: 1) after the DP moves south away from the Canadian Prairie or, 2) as the DT air cools with advections northward due to a relatively strong jet stream. The MP air mass type is linked to the mP type in that it contains air that is cold and humid. MP air is responsible for much of the wet winter weather experienced across the Pacific Northwest. MM air is warmer and often

even more humid than MP. Like the Bergeron mT air, the MT air mass type has the warmest and most humid air and is often considered to bring about the most uncomfortable summer weather along the East coast. The transitional (TR) air mass type occurs whenever air masses are changing in the area and no one type is dominant.

Kalkstein *et al.* (1990) assessed the relationship between SSC air mass frequency (in a version that has since seen updating) and climate change over the past 40 years in the United States. The results indicate that while rising temperatures have been observed, many cold air masses declined in concert with an increase in warm air mass types in recent decades. This information provides important evidence that air mass types of the SSC can be connected to important meteorological and climatological phenomena across the country, which may be useful for forecasters.

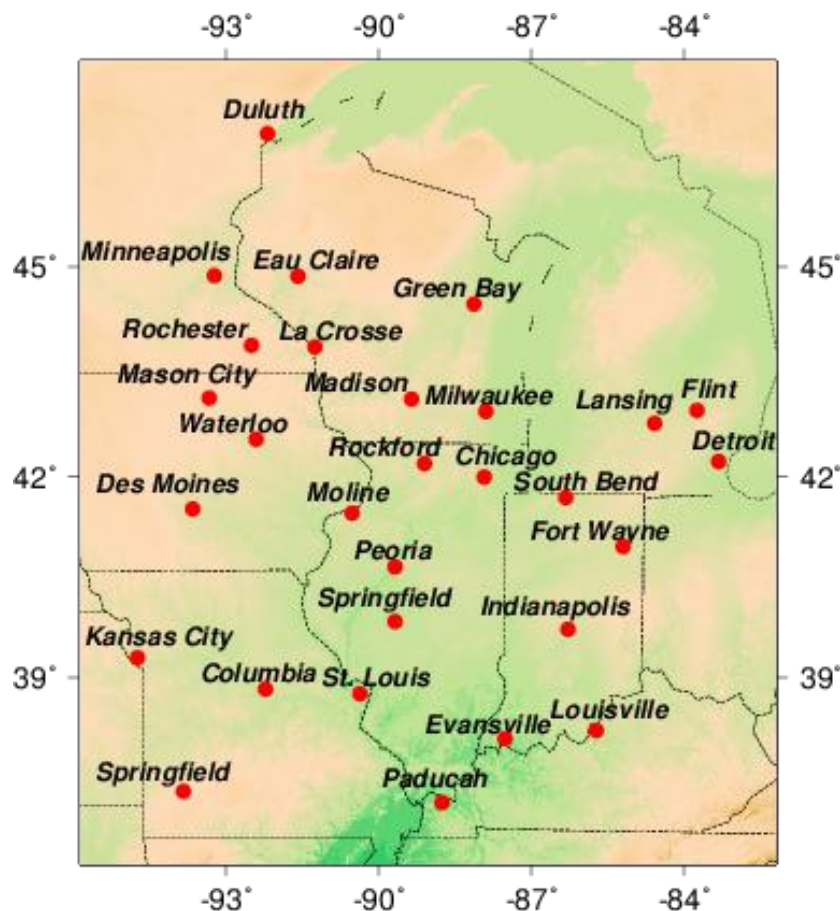
Sheridan (2002) also applied the SSC to find a relationship between air mass frequency and extreme, life-threatening heat conditions around the United States and in several high-population international cities that experience recurring heat waves. Results indicate that there is a strong connection between the DT and MT air mass type and excessive heat conditions that caused fatalities during a heat wave in Rome, Italy. The MT type was also linked to excessive heat in Shanghai, China. Similar methodologies to this investigation of extreme heat waves will be used here to examine the relationship of air masses and extreme droughts.

## METHODS AND ANALYSIS

### Study Region and Data

In order to examine the last decade of extreme drought in the Midwest from a synoptic perspective, it is important to define the region given spatially consistent meteorological and geographical patterns rather than arbitrary political boundaries. In defining this study region, latitude and longitude boundaries are chosen in order to center the region and to distinguish drought episodes in the Midwest from those in other regions. For example, southeastern Kentucky and Ohio exhibit similar temporal drought tendencies to the Southeast region even though the USDM identifies these as Midwest states. USDM regional and state graphs, tables and maps that depict the timing of drought are used to identify this cohesion. The regional boundaries identified here are 36.5°- 47°N and 85°- 96°W. These selection criteria resulted in 29 high-quality SSC stations (less than 3% missing data over the last decade) located within Minnesota, Wisconsin, Iowa, Missouri, Illinois, Indiana, Michigan and Kentucky (Fig. 2). Two stations slightly outside of the regional boundary (Flint, MI and Detroit, MI) were included in order to maintain no more than 3% missing data for any station. Daily SSC air mass data are collected for these sites (Sheridan, 2011), for 2000 – 2010 in order to establish the general air mass pattern over the period of study for each particular location.





**Figure 2.** Midwest Study region station locations (created at USGS 2010).

### Extreme Drought Episodes

After selecting stations, drought episodes are established for the entire region. These episodes are based on the suite of USDM states included in the Midwest region. It is deemed beneficial to utilize the entire region in selecting drought episodes so that individual state variations do not contribute to the elimination of drought days which most states experience. In addition, air masses are often advected across large regions versus individual states which is the scenario examined here for relationships to regional droughts. To select droughts, Severe (D2) and Extreme (D3) drought

criteria are scrutinized to select only the most robust signature of drought days across the region. Individual days are classed as a drought episode if: 1) some percentage of the Midwest region experienced Extreme drought conditions that day AND greater than 10% of the region experienced Severe drought that day, or 2) greater than 25% of the region experienced Severe drought on that day. These combinations of conditions are hereafter referred to as “extreme drought” episodes in this research assessment.



These criteria produced nine continuous drought events (Drought 1, 2, 3, 4a – e, and 5) across the decade with only six days that did not meet these standards. Since the drought conditions present on each of the six days was very close to the necessary analysis standards, the six days are retained for each episode. Further, the

days of Drought 4 a – e are combined into two clusters (Drought 4a and 4b) since less than a month separated the days between intervals 4a referred to as Drought 4b. Table 3 highlights the duration and season of each of the six drought episodes and the exception days.

<b>Episode</b>	<b>Year</b>	<b>Duration</b>	<b>Season</b>	<b>Exception Days</b>
<b>1</b>	2000	5/23 – 6/20	Spring/Summer	
<b>2</b>	2003	1/21 – 4/29	Winter/Spring	1:04/08, 9.59% D2
<b>3</b>	2003	9/09 – 12/30	Fall/Winter	
<b>4a</b>	2005/06	07/05/05 – 01/24/06 (4a*) 2/28 – 3/28 (4b*)	Summer/Fall/Winter Winter/Spring	4:01/03, 9.62% D2 10/04, 9.01% D2 08/30, 9.53% D2 07/12, 9.8% D2
<b>4b</b>	2006/07	7/25 – 8/22 (4c*) 9/12 – 11/28(4d*) 12/19 – 2/ 27(4e*)	Summer Fall Winter	
<b>5</b>	2007	7/24 – 10/16	Summer/Fall	1:7/31, 0% D3

**Table 3.** Extreme drought episodes in the Midwest from 2000 – 2010. \* Indicates initial identified drought episodes before merging close intervals

## Air Mass Frequency Analysis

### *Baseline Frequency Analysis.*

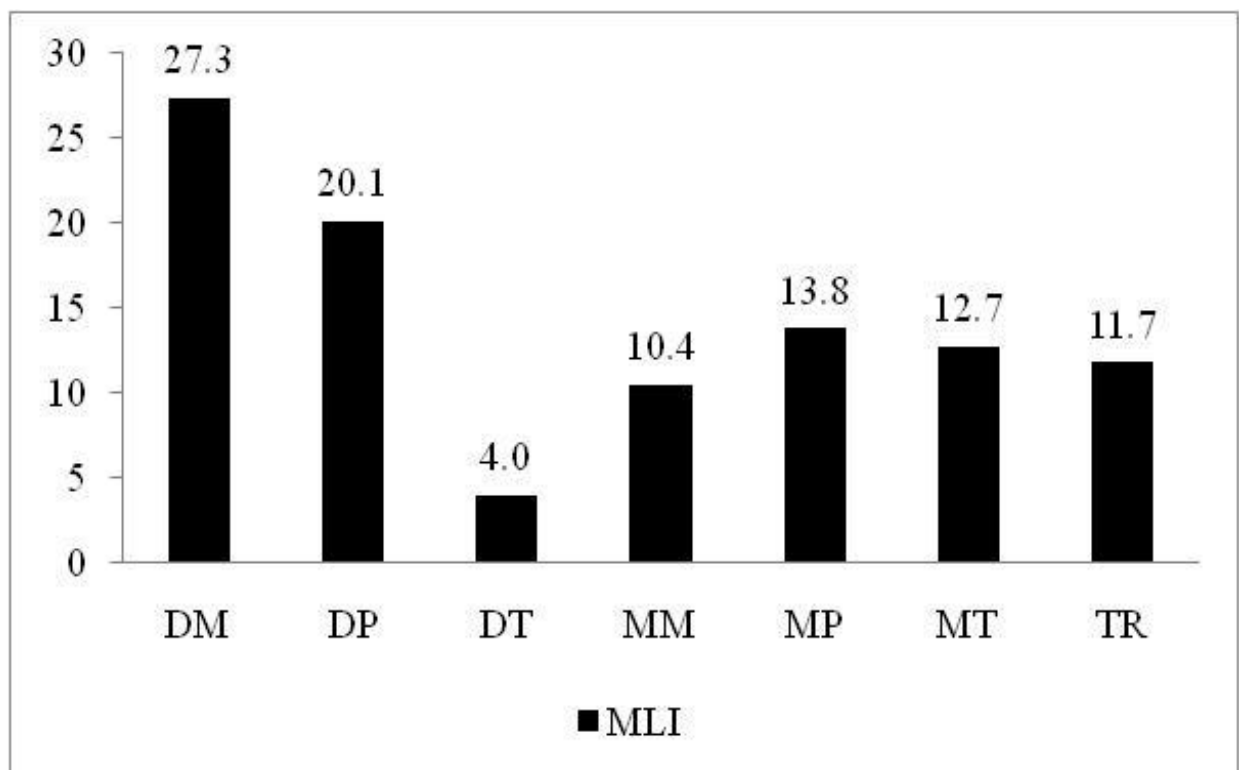
To first examine the magnitude of air mass frequency departures during extreme Midwest drought intervals, the synoptic conditions that may contribute to the onset and persistence of drought, several baseline periods are established. Frequency counts and percentages are calculated for all SSC air mass types for the duration of each baseline (with one exception at Kansas City where the station record only extended to 1972). These baselines are representative of

the "normal" synoptic conditions at a station location and, as such, describe average air mass frequency for: 1) the long-term period of record from 1950 – 2010, 2) the last decade from 2000 – 2010 and 3) individual seasons over the last decade.

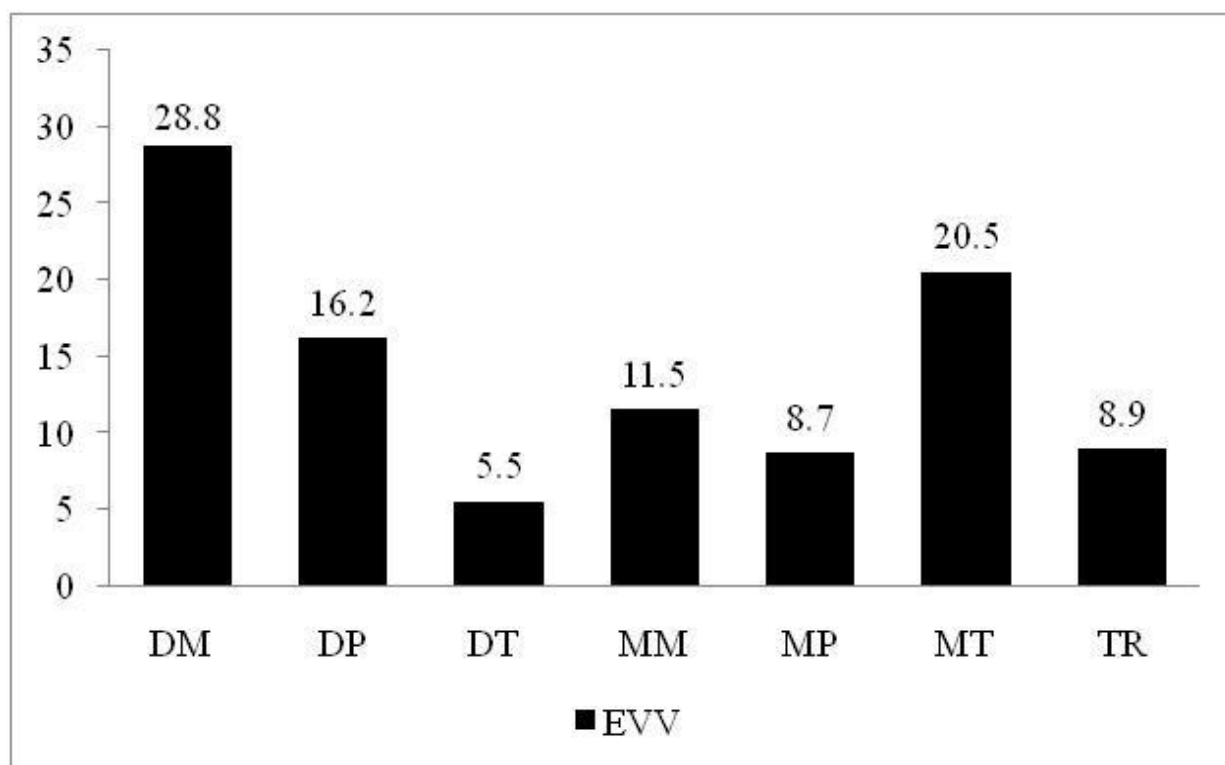
It is important to consider the advantages of declaring several normal intervals in this analysis. A long-range air mass normal, such as that of a 60-year period, is most indicative of the average synoptic climatology of stations across the Midwest region (fig. 3). Long-term record assessments also reduce the contribution of anomalously wet and dry year bias to the

average frequency calculations. Alternatively, the study period covers a 10-year interval and it is deemed equally important to have the ability to analyze the 10-year air mass tendencies against the longer climatology (fig. 4). It should be noted that a dry decade may decrease the detectable magnitude of frequency variation during extreme drought. Nevertheless, if significant air mass frequency variability is observed against a dry period, these findings indicate that a similar but amplified tendency could be found with the period of record. In other words, if increased dry air

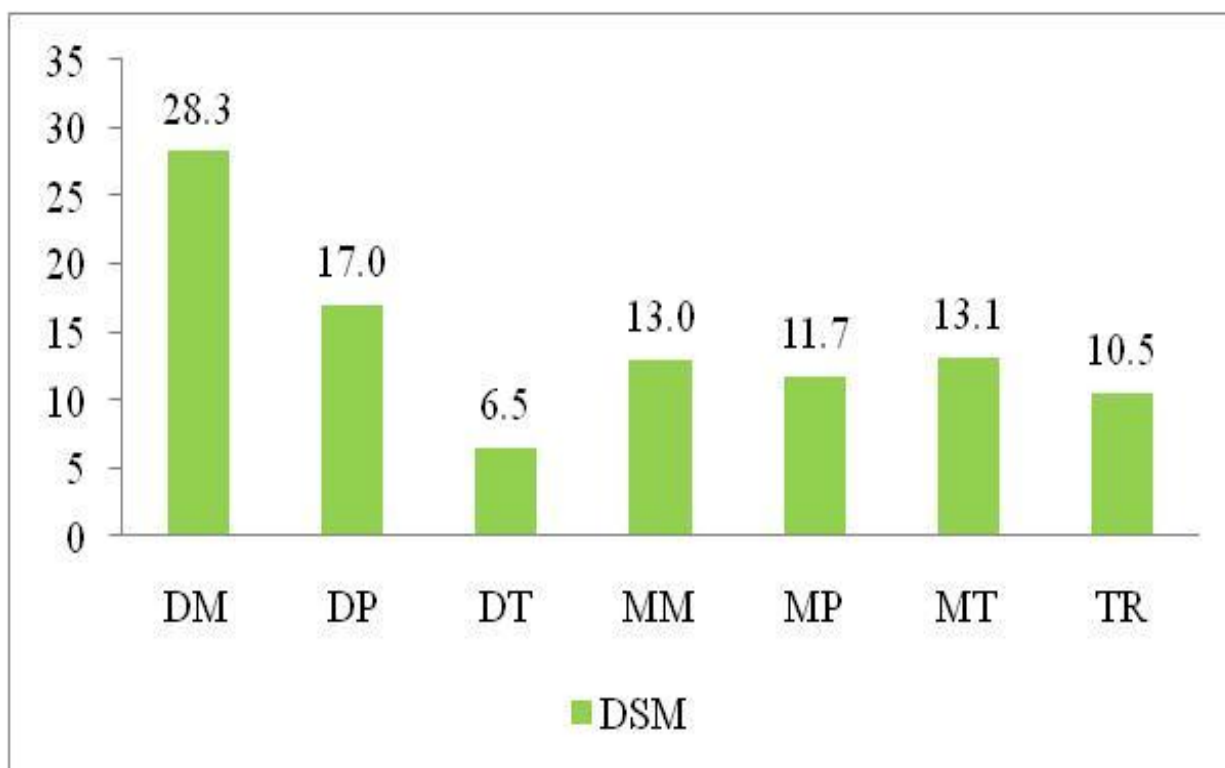
mass frequency departs from that of a dry decade, then an even larger departure is expected from the long-term normal which makes this baseline a robust measure of extreme drought departures. Finally, since air mass patterns naturally vary by season, a seasonal frequency assessment is also conducted for each location. Figure 5 depicts one example acquired at Des Moines in spring. Seasons are defined annually in three-month intervals, starting in December (Winter: DJF, Spring: MAM, Summer: JJA, Fall: SON).



**Figure 3.** 1950 – 2010 air mass frequency (%) at Moline, IL.



**Figure 4.** 2000 – 2010 air mass frequency (%) at Evansville, IN.

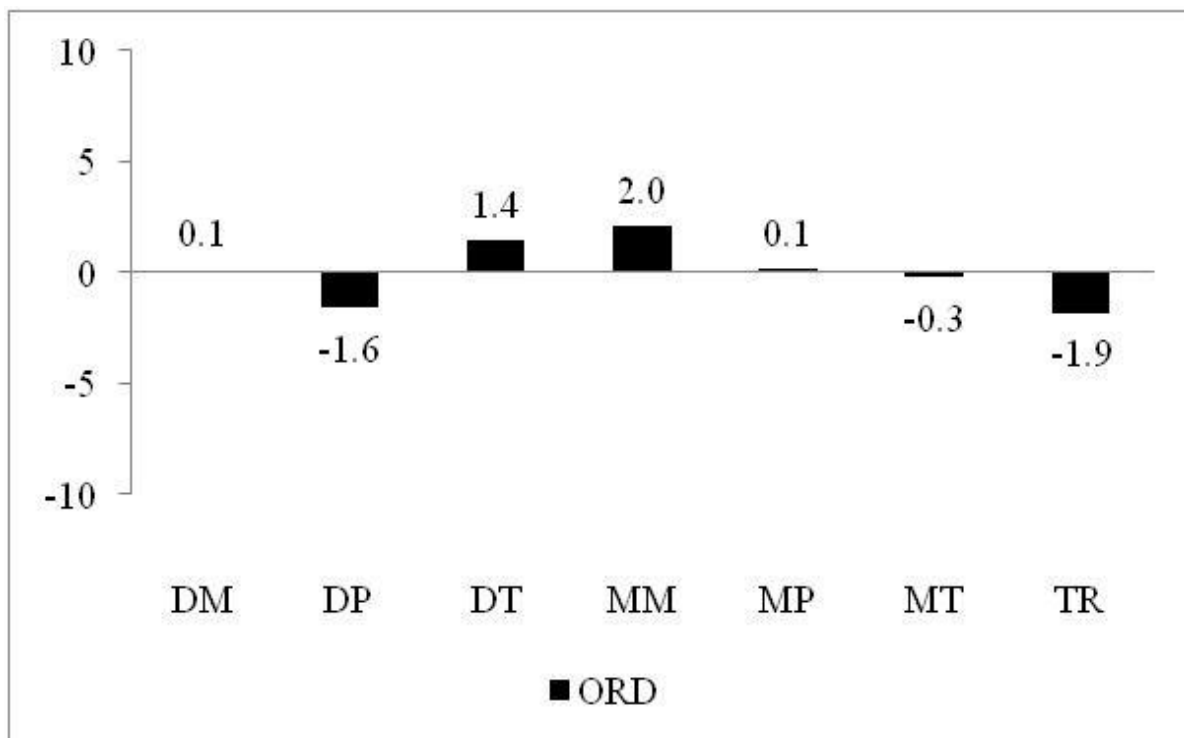


**Figure 5.** 2000 – 2010 Spring season air mass frequency (%) at Des Moines, IA.

### ***Drought Frequency & Difference Analysis.***

After baseline periods are identified, an additional frequency analysis is performed for all air masses during drought event days. To do this, all days classed in drought episodes 1 – 5 are grouped together so that a large set of days (stations average near 719 total drought days) are represented as extreme drought to compare to the baseline. Combining all drought days together is also useful so that a general and robust synoptic pattern can be identified if individual droughts are not clearly demonstrating the same air mass tendencies. Next, the total frequency of each air mass was determined for the new drought category. These frequencies are compared to baseline values to identify the magnitude of the air mass departures during drought events. Here, frequency differences are

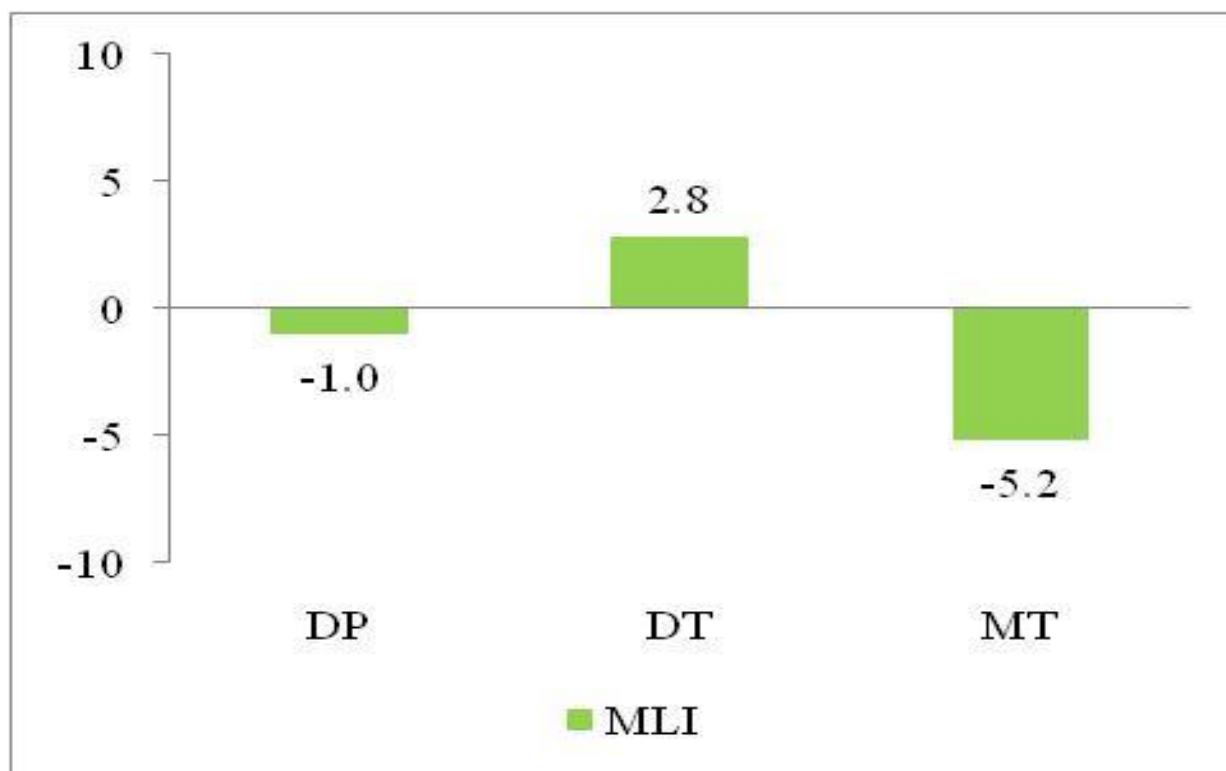
calculated against the decadal baseline (fig. 6). Though it is worthwhile to compare these frequencies to all baseline periods for a comprehensive set of results, it is simply beyond the scope of this research to perform all of those difference assessments. Instead, the decadal baseline is chosen since the frequencies very closely represent those obtained for the last 60 years (Fig. 3 and 4). In addition, this period directly overlaps the available drought USDM record. Since the primary difference observed between the decade and the entire period of record lies in more frequent dry air mass days over the past 10 years, the DM, DP, and DT departures that are acquired are likely fainter than those that would be obtained if the period of record baseline were to be used. This may also be the case where less moist air masses are detected.



**Figure 6.** Drought episode air mass frequency departures (%) at Chicago, IL.

After obtaining the drought frequency differences, results at each station are compared to identify spatially consistent patterns across the region. This process allowed for the selection of three air masses to be further evaluated against the seasonal baseline for seasonal air mass frequency departures during times of drought (fig. 7). It is beneficial to perform a seasonal difference assessment to gain more specific information on the synoptic conditions present during drought, especially since droughts in the Midwest do not occur at any

one time of year but across all seasons. Here, any unique air mass tendencies that occur during droughts in one season but not in another may be highlighted. For instance, it may be the case that dry moderate air masses are much more frequent during extreme winter droughts, but in spring, extreme droughts coincide with far fewer moist tropical air masses moving into the Midwest. This distinction is important for improving seasonal and annual drought predictions.



**Figure 7.** Drought episode Spring season air mass frequency departures (%) at Moline, IL.

Overall, the DP, DT and MT air masses are identified for additional seasonal frequency departure assessments. Table 4 highlights the important criteria that allowed for these air masses to be chosen. It is

interesting to note that these air masses did not appear to be the only types that exhibit practically significant departures during times of drought. For instance, the DM air mass displays the same tendencies as the DP

but with less magnitude at most stations. Therefore, it may be expected that the results of the DM and DP exhibit similar seasonal frequency tendencies with similar practical significance, but perhaps without statistical significance. Collectively, the findings of the decadal departures and selection of the three air mass types indicate that some positive and negative frequency departures correspond. For instance, while dry air masses are always present across the Midwest, the DP air masses are less frequent during drought while the DT are more frequent. This means the region, annually, is hotter and drier than normal during extreme drought.

The statistical significance of the percentage of air masses present was assessed. To do this, a two sample test of two proportions was used. Doing this creates a z-value for each station, using air masses deemed most important for the seasonal frequencies and also for the decadal frequencies. Once the z-value is acquired, as well as the amount of data going into the calculation, the statistical significance can be determined. Individual stations showed more statistical significance than others, showing that certain air masses tended to be more important than others.

<b>Air Mass</b>	<b>Explanation for seasonal air mass frequency difference analyses</b>
<b>DP</b>	significant negative frequency departures during drought at most stations
<b>DT</b>	significant positive frequency departures during drought at most stations
<b>MT</b>	significant negative frequency departures during drought at most stations

**Table 4.** Air masses selected for seasonal drought frequency departures with explanations.

## RESULTS

In order to determine the relationship between particular air masses and the occurrence of drought in the Midwest, baseline frequency analyses are performed to identify regional synoptic normals. These air mass frequencies are compared to those during times of widespread and extreme regional droughts and the differences are examined to view changes in the synoptic conditions during these events. The statistical significance of these air mass departures was calculated. The results of both assessments are outlined below.

Generally, the results of this decadal assessment indicate that there is a strong relationship between air mass frequency departures, specifically seasonal frequency variability, and extreme drought in the Midwest. The major findings of the decadal assessment indicate that drought, as expected, is associated with an increase in dry air masses, specifically the DT. The seasonal assessment indicates that the signal of drought may be detected most notably in increases of the DT air mass and decreases in both the DP and MT air mass types.

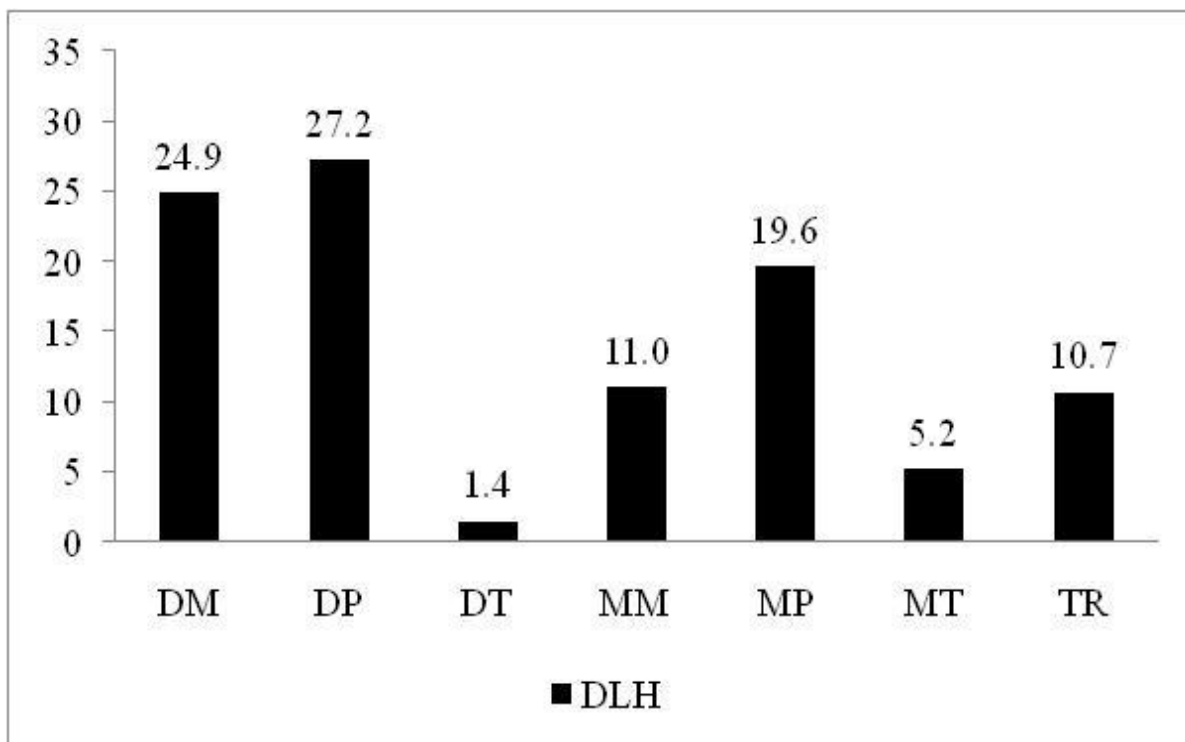


## Annual Air Mass Frequency

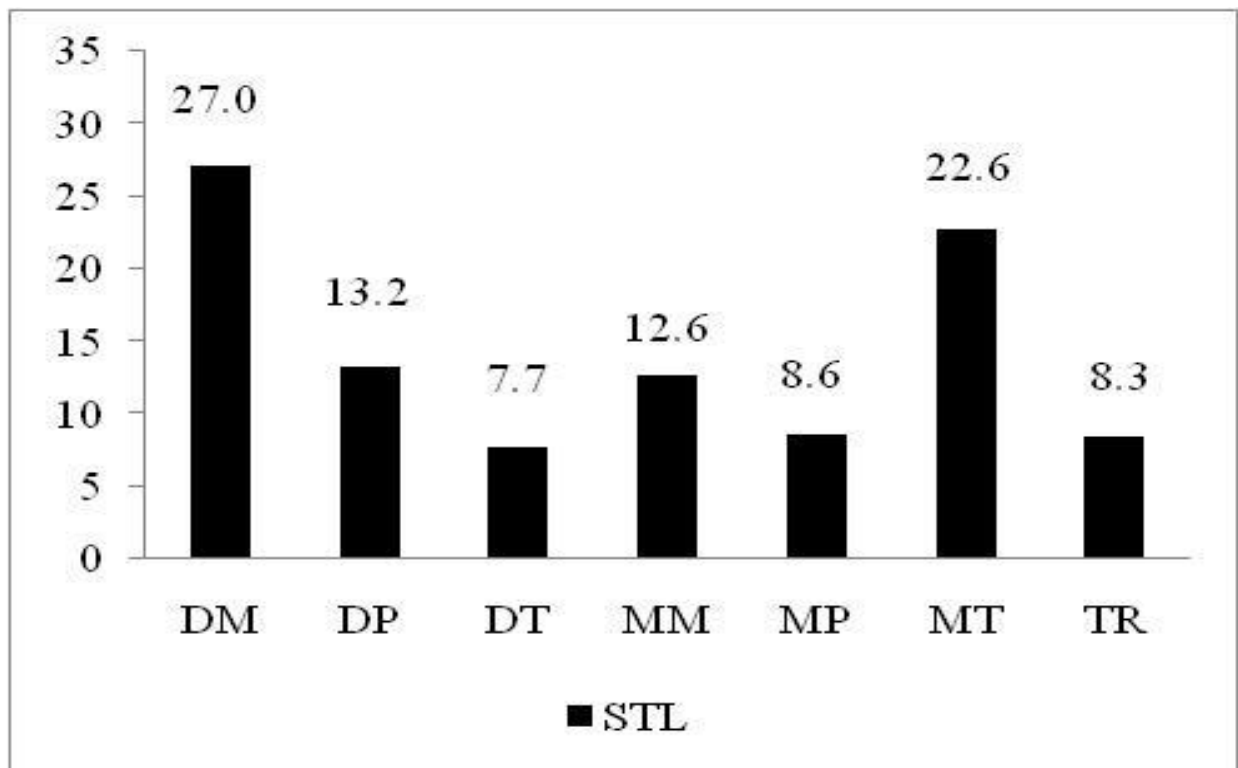
### *The Decade.*

For nearly all stations in the Midwest, the DM is the most frequent annually-occurring air mass and the DT is the least frequent at all stations (fig. 4). The frequency range for DM is approximately 25-35% of all air mass days whereas frequency ranges from 1-5% for DT. At extreme northern locations within the region, DM is the second most frequent air mass while the DP air mass is annually the most numerous. This tendency is evident in Figure 8 for a station in northern Minnesota. The result is not surprising, as the northern reaches of the region are expected to receive more influence from colder Canadian Prairie air masses throughout the year. Interestingly, throughout the year the MP air

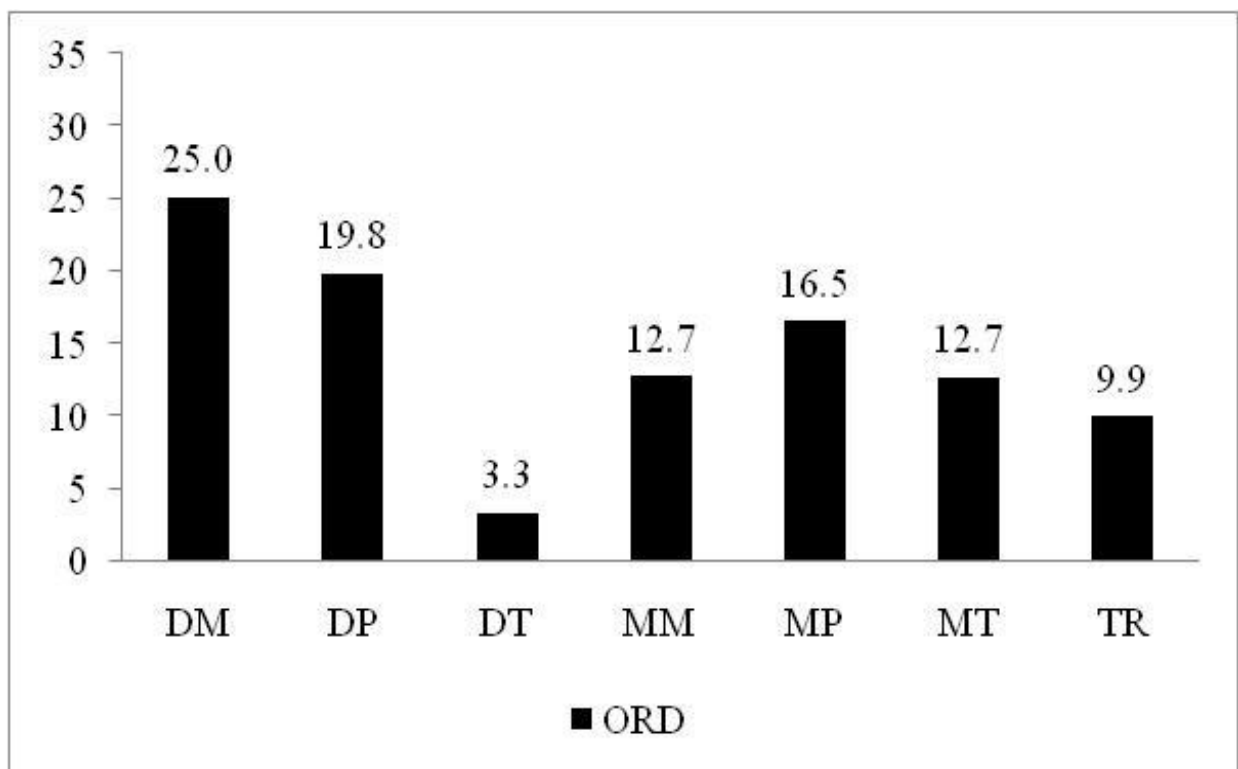
mass is not a significant presence. On average, MP accounts for approximately 15% of all air mass days. This result indicates that the Great Lakes may not be contributing ample moisture totals to the air that most often occupies the Midwest region. There are other inconsistencies in the second most frequent air mass, which appear to exhibit more spatial tendencies. The MT is the second most prevalent type in southern sections of the Midwest, such as in St. Louis (fig. 9) while most northern and central areas of Midwest have the DP air mass as the second most numerous (fig. 10). This result is intuitive, since warm, moist air masses from the Gulf are likely more influential across southern sections of the Midwest than cold, northern air masses. For all locations, the MM and TR air mass frequencies varied in between these values, ranging from approximately 10-15%.



**Figure 8.** 2000 – 2010 air mass frequency (%) at Duluth, MN.



**Figure 9.** 2000 – 2010 air mass frequency (%) at St. Louis, MO.

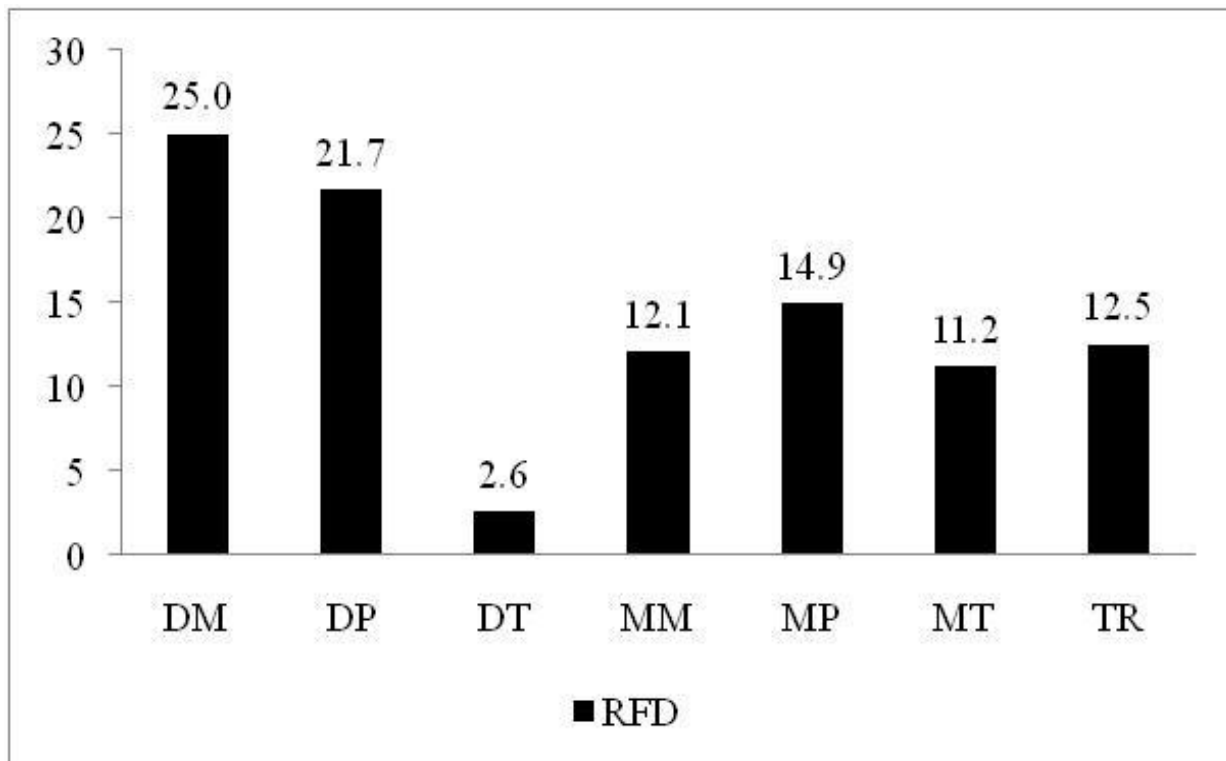


**Figure 10.** 2000 – 2010 air mass frequency (%) at Chicago, IL.

### ***Period of Record.***

The 60-year annual air mass frequencies show similar tendencies to the 10-year analysis results. In general, the most and least frequent air mass for Midwest stations are again DM and DT, respectively (fig. 11). The frequency range for DM is 20-30% and, consistent with decadal findings, DT air mass frequency is 1 – 5%. Recall that the frequency range for DM in the 10-year frequency analysis was 25- 35%. This result indicates that the last decade received more dry air masses (at least more DM air masses) than in previous decades. In other words, the 10-year analysis represents an overall dry period compared to the 60-year period. The spatial tendencies of the second

most numerous air masses are consistent with those mentioned in the previous section. Extreme northern sections show that DP surpasses DM as the most frequent air mass. This tendency is dissimilar to most central and southern Midwest areas that depict the MT as the second most frequent air mass type. Despite the aforementioned discrepancy in the frequency range of DM, the difference is approximately 5%. This difference is deemed negligible in considering the decade frequencies as accurate representations of the normal regional air mass tendencies.



**Figure 11.** 1950 – 2010 air mass frequency (%) at Rockford, IL.

## Seasonal Air Mass Frequency

### *The Decade: Spring.*

In the springtime, the most common air mass at all stations across the region is the dry DM air mass type, with 25- 34% frequency at most stations. The second most prominent air mass is either MP or MT moist air mass varieties, depending on the station. At more northern locations, the MP generally represents the second most prevalent type. This tendency may be related to the cold, lingering impact of winter air masses in the northern locations. However, this also is indicative of the significant Great Lakes influence on air masses as a moisture source in spring (even with cooler air temperatures).

At southerly stations, springtime means the MT air masses are the second most prominent type (fig. 12). This result indicates that warm, moist air masses from the Gulf of Mexico and the Atlantic Ocean are migrating northward to the Midwest at this time of year. However, the spring still sees more dry DM air masses than moist, even in the southern reaches. The least common air mass at most stations (especially in the north) is the DT with less than 5% at all stations and no other clear air mass tendencies are identified. This result may indicate that air from the dry continental Southwest and Mexican plateau is prevented from entering the region in spring, perhaps due to an amplified meridional jet stream pattern.

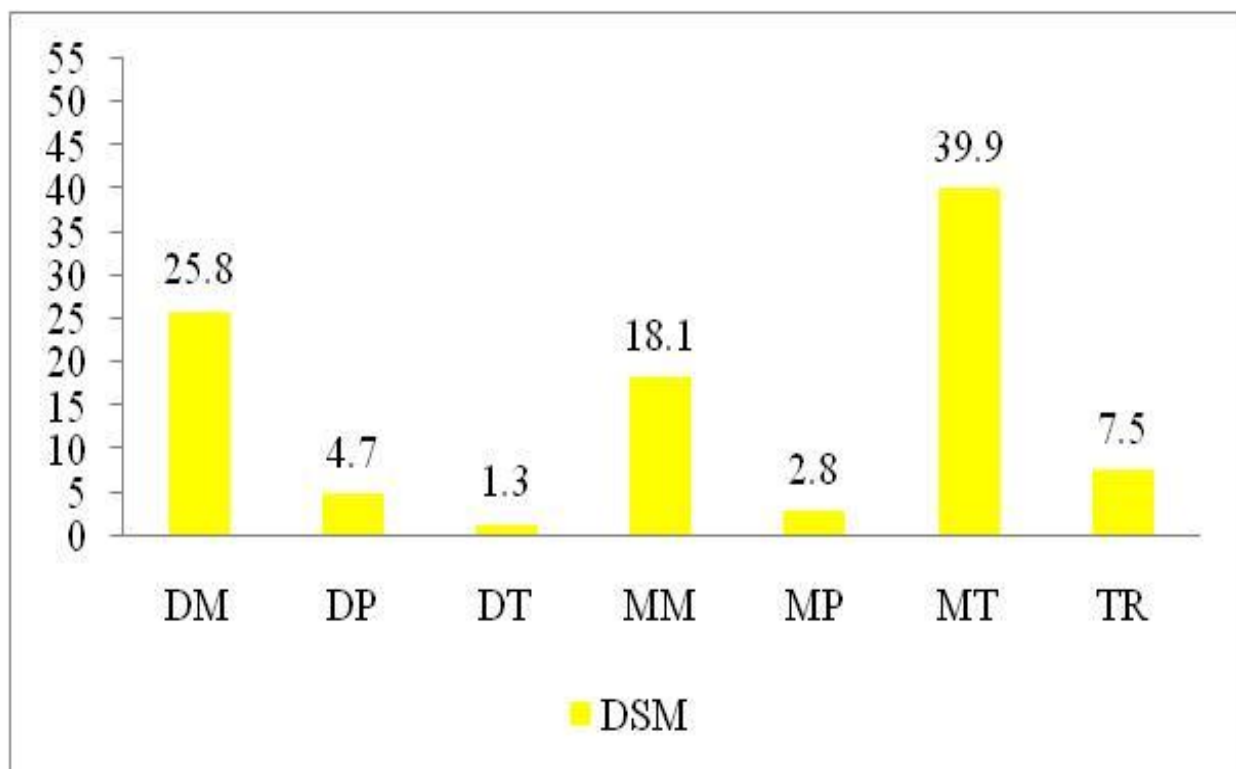


**Figure 12.** 2000 – 2010 spring season air mass frequency (%) at Louisville, KY.

### ***The Decade: Summer.***

In the summer season, the most common air mass at all locations is the moist, hot MT variety with 45% frequencies on average, especially in the south. These values decrease slightly, to 30% at northern locations. The MT is typically followed by the dry DM air mass which is the most prevalent in the spring season that gives way to summer (fig. 13). Therefore, it appears that the DM declines in Midwest summers (which is not apparent in the annual frequency results) and this result also indicates that the southern Gulf of Mexico

advections of air masses into the region are a more dominant forcing in the summer season than in the springtime (*i.e.*, compare Figures 5 and 13 at Des Moines). Warm air masses generally dominate the region in summer while cool air mass varieties (DP and MP) are far less frequent than in spring. The MM air mass is also rather frequent across the region at many locations, often appearing in the first three most prominent air mass varieties in summer. Similar to the springtime results, the least common air mass is DT (4% average frequencies) followed by MP (7% average frequencies) at most stations.

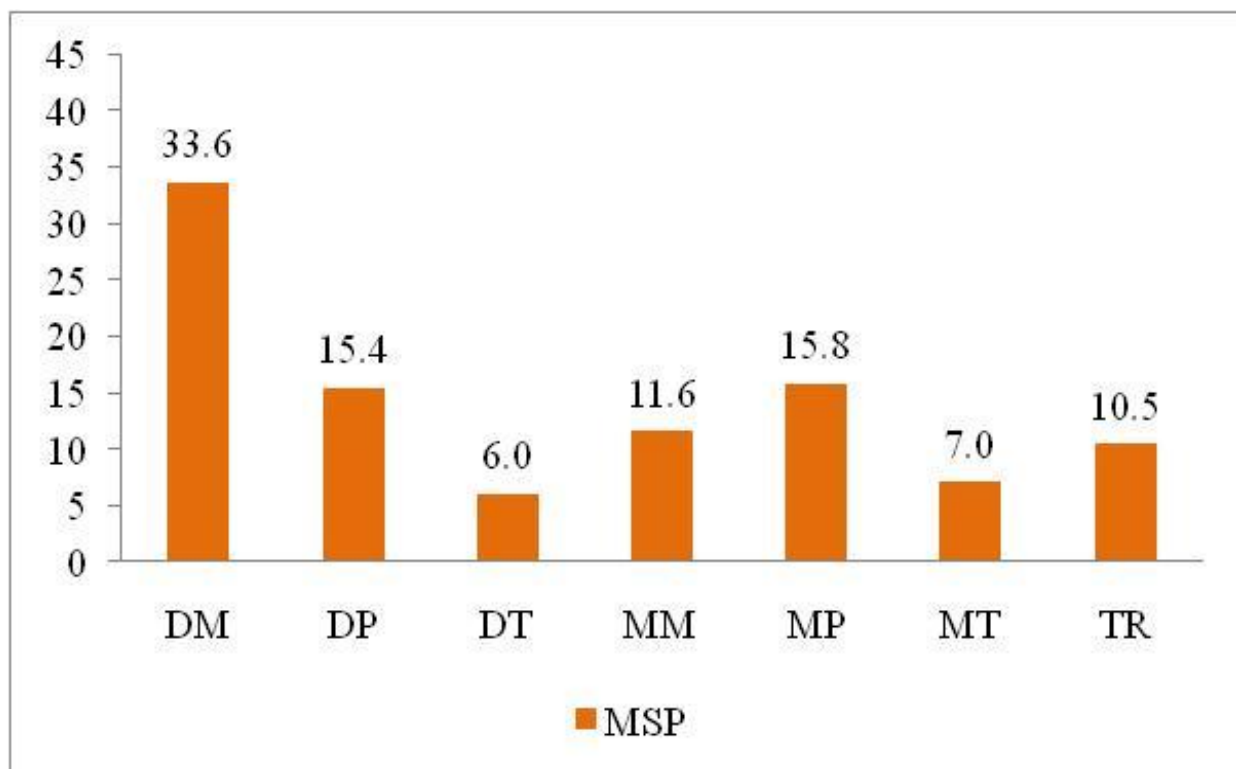


**Figure 13.** 2000 – 2010 summer season air mass frequency (%) at Des Moines, IA.

### ***The Decade: Fall.***

The fall season is a synoptically dry time for the Midwest, with the DM and DP generally tending toward the first and second most common air masses, respectively. At northern locations, the MP air mass is often the second most frequent variety (fig. 14). DM is always the most frequent (26-36%) while the DP and MP vary between 15- 25%, depending on station. This result indicates that even while the season is dry, the cooler air mass types are more dominant than in summer. At this time of year, the tropical air mass types are

also less frequent than in the summer season. Northern stations have higher polar air mass type frequencies than detected at southern locations. This may be due to the amount of time necessary for a cold Canadian or Great Lakes air mass to advect south and the dominant jet stream pattern. For instance, more zonal jet stream patterns or amplified ridges in the Southeast may keep these air masses from reaching the southern Midwest. In fall, the least common type is DT, and the second least common varied considerably between individual stations.



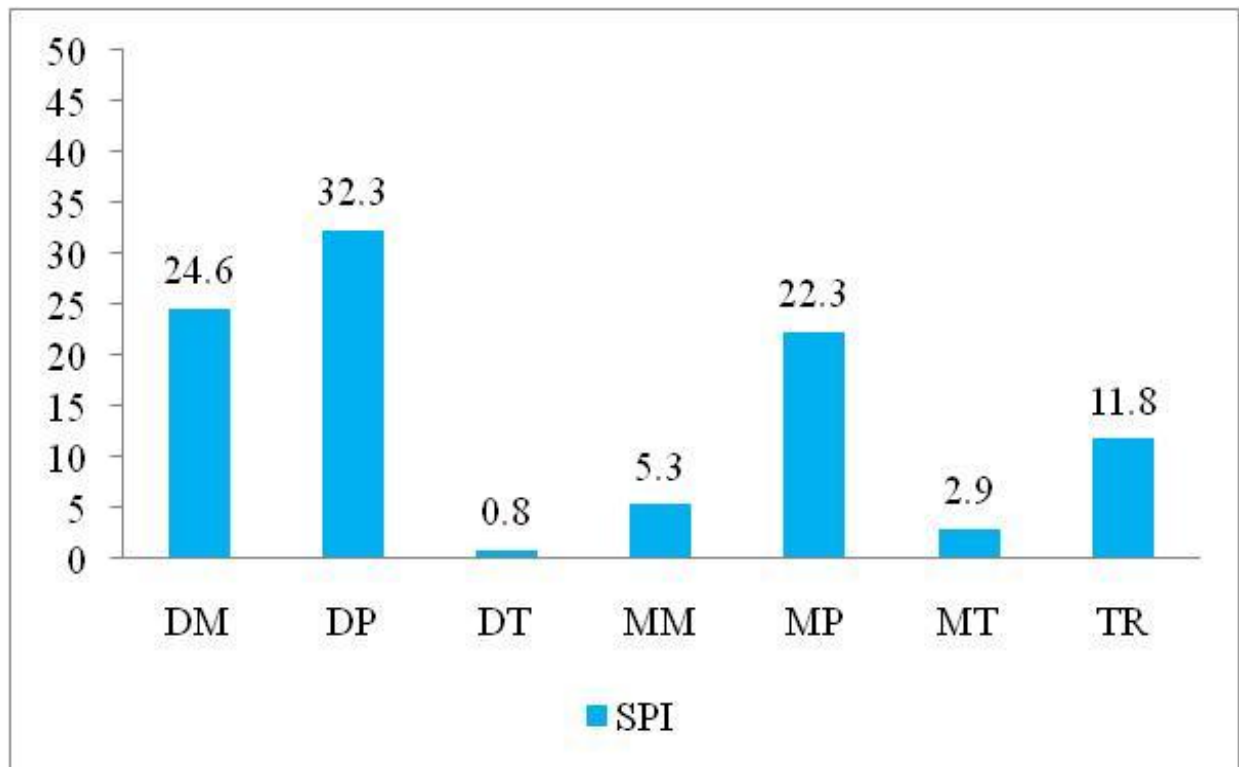
**Figure 14.** 2000 – 2010 fall season air mass frequency (%) at Minneapolis-St. Paul, MN.



### ***The Decade: Winter.***

The coldest air mass varieties in the SSC, the DP and MP types are the most and second most common in Midwest winters, respectively (fig. 15). Polar air masses dominate the entire region with frequencies approaching 40%, while tropical air masses are almost non-existent in the north. This may be due to the presence of a pronounced trough that extends into the farthest southern reaches of the region for most, if not all, of the season. Toward the south, however,

moderate air masses tend to be slightly more frequent. Perhaps this finding indicates that the winter upper-air flow pattern acts to keep the cold and warm air mass types separate where cold air masses remain to the north and warm air masses remain south. This could occur with zonal flow situated right across the Midwest or with a ridge-building event over the south. The least common air mass is DT (frequencies less than 4%) followed by MT (frequencies less than 5%) in all areas.

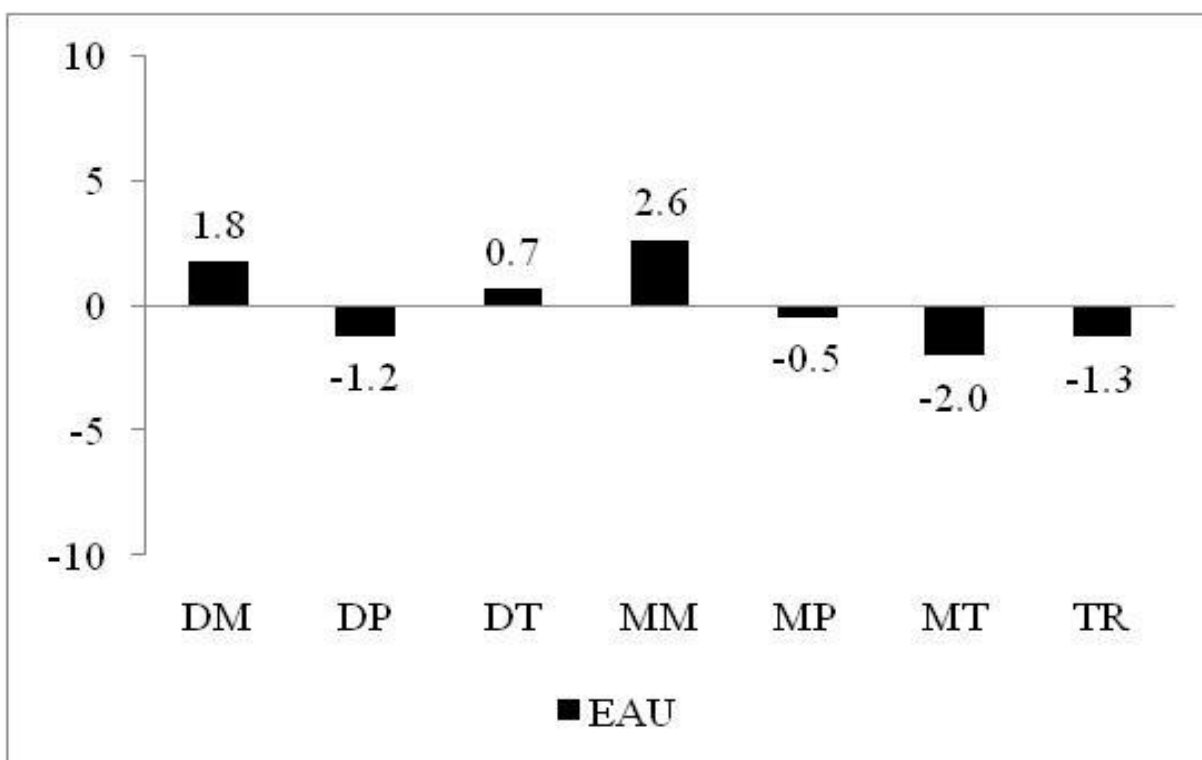


**Figure 15.** 2000-2010 Springfield, IL winter air mass frequency (%).

## Decadal Drought Frequency Departures

Air mass frequency differences are calculated and tested for statistical significance at each station to determine the magnitude of the departure. During times of extreme drought, the DM air mass increases for a majority of the stations, ranging from 0.1-8.4% (fig. 16). The only substantially different finding is detected at Des Moines in which a decrease of 1.3% is observed. DM frequency departures are not deemed statistically significant. The DP air mass decreases by 0.1-2.5% across the region during the drought periods. Like DM, these

changes are not found to be statistically significant. However, the DT air mass displays statistically significant frequency increases at the 95 and 99% confidence levels across the region (i.e., Minneapolis-St. Paul, Waterloo, Kansas City, Chicago, Moline and Peoria) during the period, ranging from 0.3-5.4%. This result shows that the influence of air mass thermal properties may also contribute to drought occurrence, along with the expected moisture properties. In other words, an increase of hot, dry air at these times may be entering the region from the southwest.



**Figure 16.** 2000 – 2010 frequency differences (%) at Eau Claire, WI during drought.

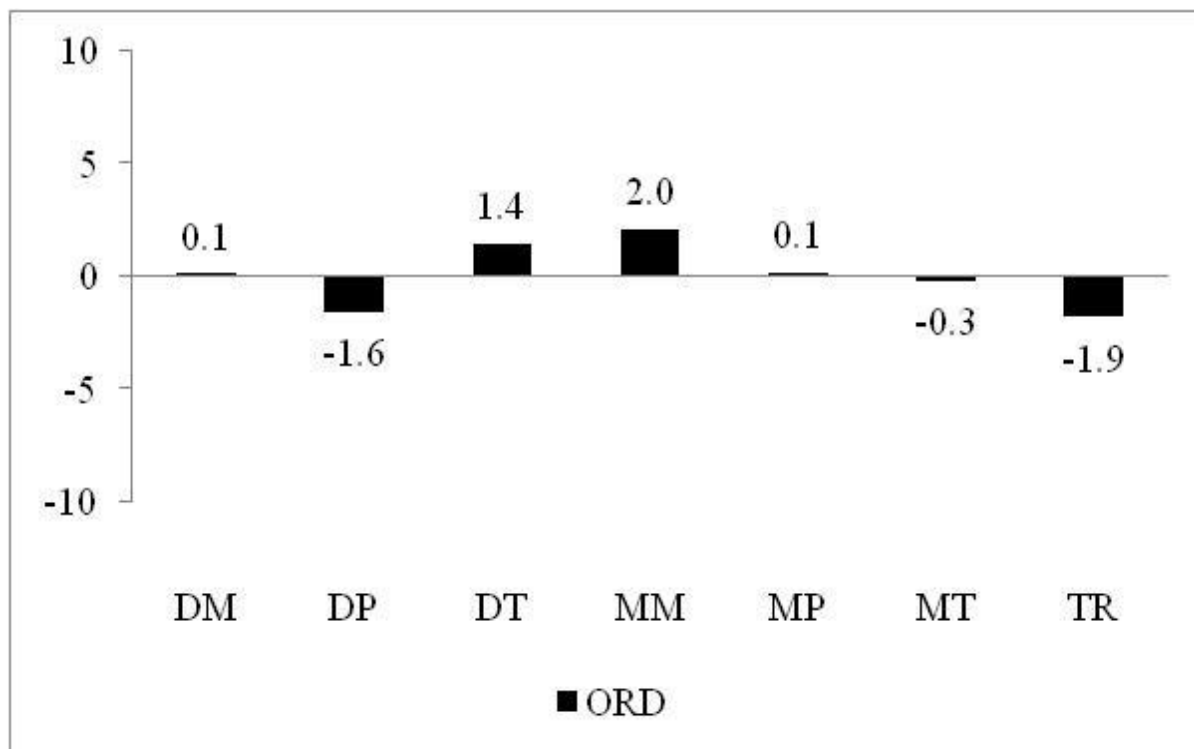
The decrease in the cooler DP air mass type during drought is matched by the increase in the warmer DT air mass type which may mean that drought periods, regardless of season are actually warmer

than average across the Midwest. Both air mass types are dry varieties that are predominant during extreme drought and across the dry decadal period, which is a finding that matches the early hypotheses of

this research. It is because of this noted relationship that both the DP and DT air mass types were selected for further evaluation in seasonal frequency difference assessments.

The differences detected for moist air mass varieties include the MM air mass type with nearly equivalent (and small percentage) increases and decreases during drought events (fig. 17). At the 95% confidence level, the positive frequency departures at Rochester and Eau Claire are found to be statistically significant. It is determined that this tendency may be a product of moderating influences from the Great Lakes that regularly supply moisture to the region and regulate the thermal properties of many air mass types. The MP air mass type is evenly distributed across the region in terms of increases and decreases

during drought. No departures are identified as statistically significant for this air mass type. Since the MP is always infrequent across the region, this finding may represent inherent synoptic variability. The MT air mass exhibits substantial decreases (between 0.1-4.6%) during drought events. These departures are statistically significant at the 90 and 95% confidence levels at many stations, including Evansville, IN, Columbia, MO, St. Louis, MO, Paducah, KY, Flint, MI and Rockford, IL. Only at Indianapolis are frequency increases identified. This air mass tendency supports the early hypotheses and expectations that moist air masses are less frequent during periods of drought. For these reasons, MT is selected as the third and final air mass type that will be used in performing a seasonal drought frequency departure assessment.



**Figure 17.** 2000 – 2010 frequency differences (%) at Chicago, IL during drought.

At Duluth, MN and La Crosse, WI a decrease in the TR air mass frequency during droughts is identified as statistically significant at the 90% confidence level. This may mean that there are less fronts, storms and moist air masses passing through the

region during a drought event. In addition, more stagnant conditions may persist and perpetuate longer duration droughts as fewer TR air masses indicate there are no systems transitioning air masses.

## Seasonal Drought Frequency Departures

### *Spring Drought Frequency Departures.*

For spring drought days, the MT air mass exhibits the greatest departures from the decade frequencies, as it follows the tendency found in decadal difference assessments that MT will exhibit substantial decreases during extreme drought (fig. 18).

Nearly all of the stations show that there is up to 5% fewer MT air masses during spring droughts. For example, there is a 2.1% decrease at Rochester and a 5.2% decrease in MT air masses at Moline, IL. These findings, while perhaps practically significant, are not identified as statistically significant departures at the 90, 95 and 99% confidence levels.



**Figure 18.** 2000 – 2010 Spring season frequency differences (%) at Moline, IL during drought.

The DT air masses also follow the decadal difference tendencies that these types will increase with extreme drought, for example Des Moines, IA noted a 3.9% increase in DT. These air mass departures, like MT, are not found to be statistically significant. However, in Detroit, MI a statistically significant decrease in DT is identified that may indicate if there are fewer hot, dry air mass days the alternative dry and mild, DM air mass, may be more prevalent during drought. In future research, these air mass departures should be examined.

Statistically significant springtime increases in the DP air mass are identified (99% confidence level). Stations exhibiting this tendency include Fort Wayne, IN, Indianapolis, IN Milwaukee, WI and Flint, MI. The tendency for fewer DP air masses is seen at Chicago with a decrease of 5.7%. This result could be due to regional dependence on the DP air mass frequency

### ***Summer Drought Frequency Departures.***

For summer droughts, many stations showed statistically significant departures in air mass frequencies suggesting that summer droughts are more correlated with air mass type than other seasons. The DT air mass in particular exhibits a substantial increase in frequency from the normal decadal period at most stations. This follows the decadal difference assessment tendency that DT air masses increase at times of extreme Midwest drought (fig. 19). Differences in frequency, between stations, ranges from: -0.3% to +6.0%. At Louisville, KY for example, a statistically significant increase in DT air mass frequency is observed (99%

for drought in addition to the influence of the DM air mass which was not examined seasonally.

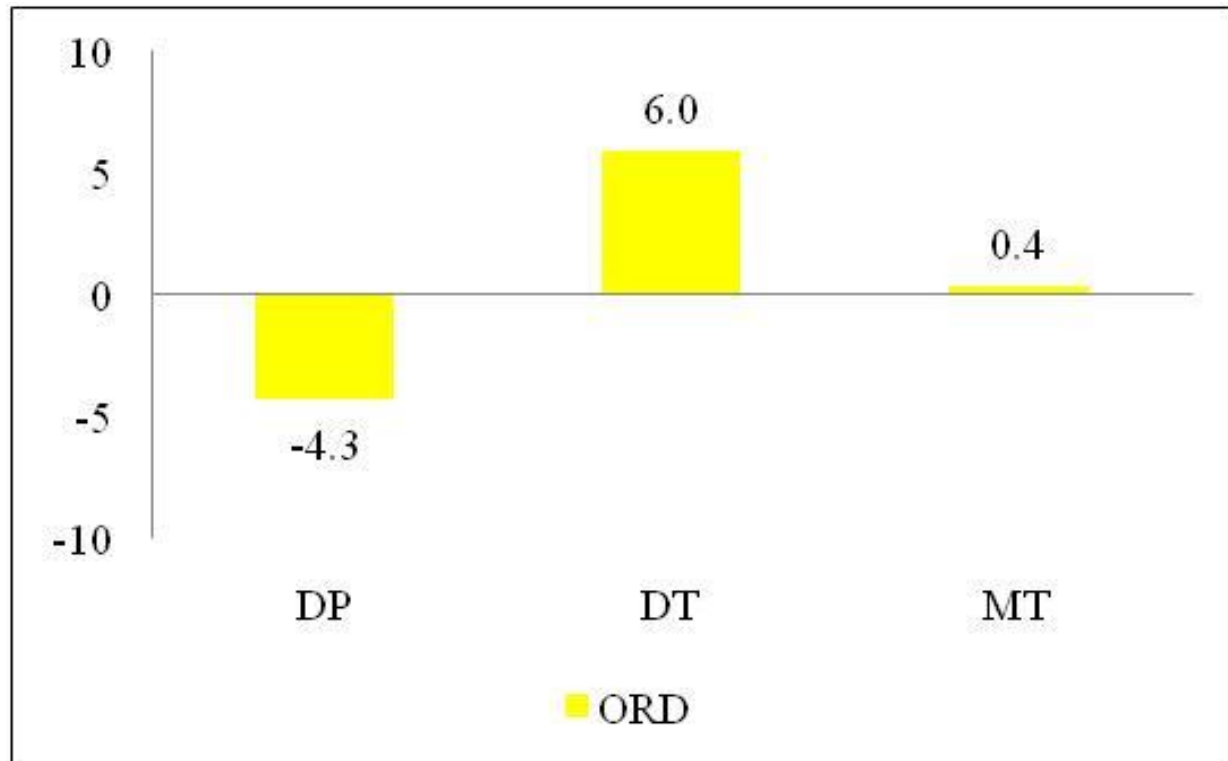
The MT air masses that generate from the southeastern region are usually only brought to the Midwest by southerly airflow. During strong springtime droughts, there is likely less southerly flow bringing warm, moist air to the Midwest. More flow from the Southwest occurs at this time, as evidenced by increases in DT air mass varieties. Generally, air from the continental southwest plateaus is hot and dry and influenced by the presence of deserts and semi-arid regions. This air is advected northeastward into the Midwest in the spring at the timing of the droughts examined here. The hot, dry air may moderate but likely adds to the perpetuation of drought conditions since no surface moisture relief comes with these air masses.

confidence level). This result is consistent with expectations for a great influx of dry air masses from the Southwest making their way into the region.

During summer droughts, the DP air mass decreases across the study region as well, which is also detected in the decadal differences. Differences range from -0.8 to -4.9% across the region. Fort Wayne, IN, Indianapolis, IN, South Bend, IN, Rockford, IL as well as Milwaukee, WI and Springfield, IL all showed significant decreases (99% confidence level) of the DP air mass. This finding likely indicates that during summer a decrease in the number of DP air masses can be attributed to the onslaught of a drought, although it should be

well-noted that DP air masses are typically rare during summer anyway. A few stations showed a significant increase in DT along

with a decrease in DP, such as Chicago and Peoria, which suggests regional dependence on the DP and DT air mass significance.



**Figure 19.** 2000 – 2010 Summer season frequency differences (%) at Chicago, IL during drought.

The MT air mass also exhibited statistically significant frequency departures. At Paducah, KY a statistically significant increase in MT (90% confidence level) and DT (99% confidence level) air mass frequencies are detected in conjunction with a statistically significant decrease in DP air mass frequency (99% confidence level). While this result is similar to other findings in that DT seemingly increased at the expense of DP, the increase in moist Gulf air masses is unexpected. It could be hypothesized that this might show that there are more warm air masses in the region, despite the moisture properties. Similarly, in

Des Moines, IA an increase in the MT air mass (90% confidence level) seems suspicious, but may occur due to the already low amount of MT air masses occurring at the station, or perhaps due to thermal rather than moisture properties. In Eau Claire, WI and Minneapolis-St. Paul, MN a decrease of the MT air mass and an increase in DT air mass (90% confidence level) were observed. These results support the hypothesis that hot, dry air from the desert southwest is replacing the warm, moist air present from the Gulf of Mexico.

Significant increases in the DT air mass could be due to zonal synoptic flow



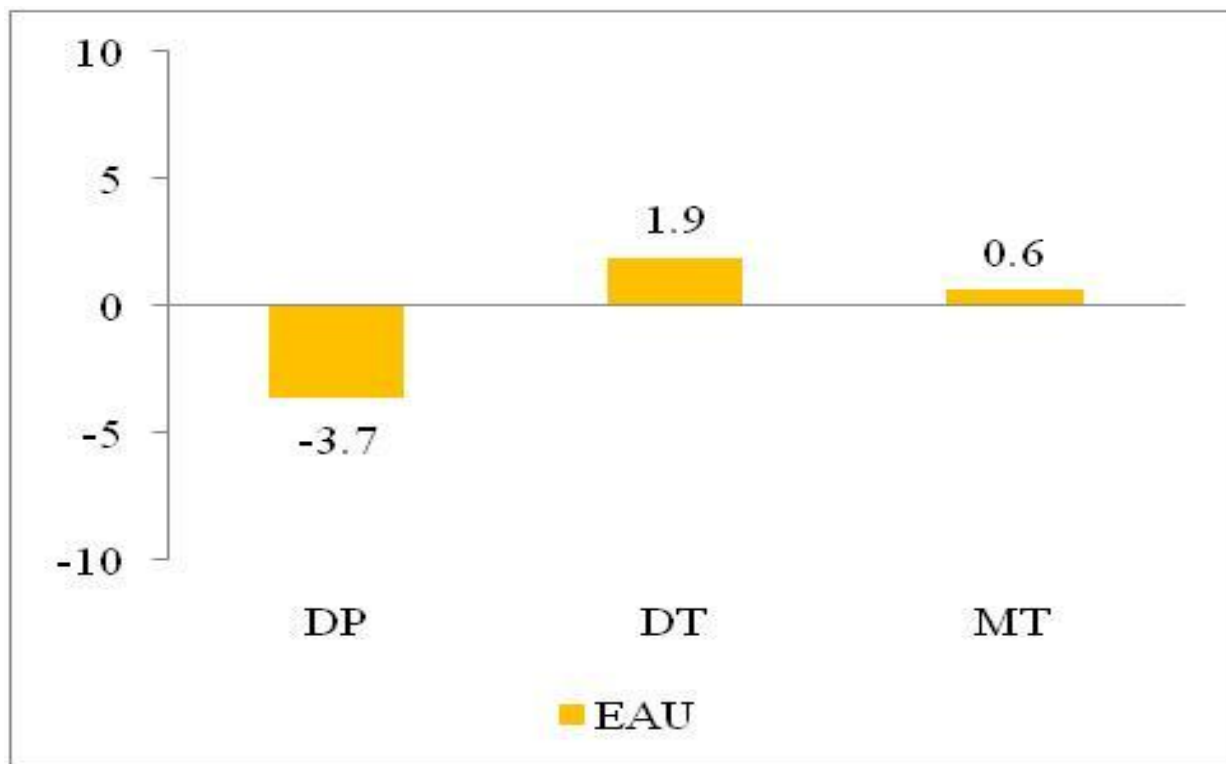
situated north of the region or a result of an upper-level ridge, centered over the Midwest, with winds coming into the region from the southwest. The stations that exhibit an exception are far northern stations, such as Duluth, MN, where only half of these locations indicate an increase in DT. Perhaps advections of DT to areas in the far

north are just too rare, even at times of extreme drought. Unlike findings for the decade departures, the MT air mass showed little variation during summer droughts. Some of the unique departures observed during summer droughts further suggest the need to determine the statistical significance of other air masses.

### ***Fall Drought Frequency Departures.***

The calculations indicate extreme fall droughts have very small MT air mass departures since most stations exhibit a low frequency of MT air masses in general throughout this season (fig. 20).

Nevertheless, MT air masses are slightly less frequent (*i.e.*, 0.6% fewer at Des Moines, IA) at most stations with exceptions in Duluth, MN and Chicago, IL. Instead, these two stations experienced increases by 1.0% and 2.9%, respectively.



**Figure 20.** 2000 – 2010 Fall season frequency differences (%) at Eau Claire, WI during drought.

Of all the dry air mass varieties, the DP air masses tend to decrease during drought while DT air masses increase. For example, the DP decreases by 3.2% at Green Bay, WI and 6.5% at Mason City, IA. The DT increases 2.1% at Minneapolis, MN and 4.4% at Moline, IL; both are statistically significant at the 95% confidence level.

This information can be interpreted as the southerly Gulf flow, which is nearly non-existent in spring, is also generally rare during the fall but perhaps slightly more prominent after a summer season that exhibited more of this type of upper-level flow pattern. The DP air mass decreases

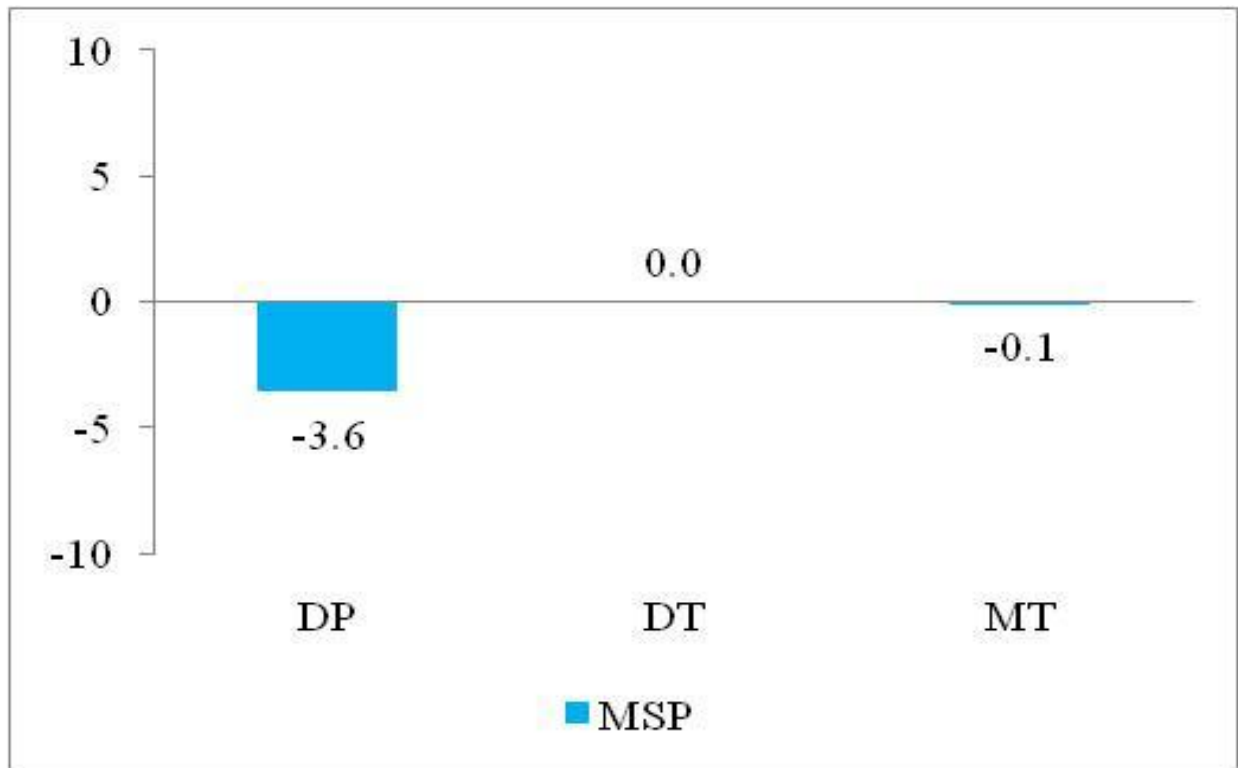
### ***Winter Drought Frequency Departures.***

For extreme droughts in winter, for most stations in the region, the DP air mass exhibits the greatest negative frequency departures from the normal period (fig. 21). This follows the tendency of the decadal difference assessment findings and differences range from -0.5 to -3.6%. MT air masses are also less frequent throughout the region, ranging from -1.2 to 1.2% fewer during drought. The tendency of DT showed little to no change in frequency. Generally, it is expected that the same synoptics as described above for other seasons may explain the decrease in DP air masses across the region in winter. Though the DM is not assessed in this seasonal difference examination, it is expected that DM air masses replace the DP air mass during

indicate that northerly flow from central Canada is not reaching the area during the fall, which would bring colder, drier air to the Midwest. Perhaps this air is kept to the north with zonal flow because the polar jet stream has not yet shifted to its most southern location (as commonly observed in winter). The DT air mass increase in frequency may support this explanation as an increase in the southwesterly flow advecting hot, dry air during the fall reaches the Midwest. Again, this pattern indicates the jet stream is still well to the north of the region.

winter drought events. This would mean that not just dry but more moderate air is present during winter drought.

In winter, Fort Wayne, IN, Indianapolis, IN, South Bend, IN, and Milwaukee, WI showed significant increases of the DP air mass with a 99% confidence level. Therefore, a direct conclusion can be made that during winter, an increase in the number of DP air masses can be attributed to the onslaught of a drought. This finding was also suggested during the spring assessment. For the stations that did not exhibit an increase in DP air masses, the DM air mass most likely played a role in winter droughts. Further assessment of the DM air mass is needed to describe the statistical significance of the DP air mass.



**Figure 21.** 2000 – 2010 Winter season frequency differences (%) at Minneapolis-St. Paul, MN during drought.

Table 5 provides a comprehensive summary of the primary findings of the current work. Foremost is the fact that the DT and MT air masses are seen to have a strong relationship with the occurrence of droughts. Second, the

DM air mass type, which was not assessed seasonally in this work, also appears to be a significant control for the occurrence of drought. These findings will be the subject of scrutiny in future work.

<b>Practically Significant</b>			
<b>Decadal Results</b>	Tendency:	Number of	Percent of
AIRMASS	Inc/Dec	Stations	Stations (%)
DM	Inc	21	72.41
DP	Inc	11	37.93
<b>DT</b>	<b>Inc</b>	<b>21</b>	<b>72.41</b>
MM	Inc	16	55.17
MP	Inc	17	58.62
MT	Inc	2	6.9
TR	Inc	16	55.17
DM	Dec	8	27.59
DP	Dec	16	55.17
DT	Dec	8	27.59
MM	Dec	12	41.38
MP	Dec	12	41.38
<b>MT</b>	<b>Dec</b>	<b>27</b>	<b>93.1</b>
TR	Dec	13	44.83

<b>Statistically Significant</b>			
<b>Decadal Results</b>	Tendency:	Number of	Percent of
AIRMASS	Inc/Dec	Stations	Stations (%)
DM	Inc	1	3.45
DP	Inc	0	0
<b>DT</b>	<b>Inc</b>	<b>11</b>	<b>37.93</b>
MM	Inc	3	10.34
MP	Inc	1	3.45
MT	Inc	0	0
TR	Inc	0	0
DM	Dec	0	0
DP	Dec	0	0
DT	Dec	1	3.45
MM	Dec	0	0
MP	Dec	0	0
<b>MT</b>	<b>Dec</b>	<b>12</b>	<b>41.38</b>
TR	Dec	2	6.9

**Table 5.** Practically (top) and statistically (bottom) significant decadal air mass frequency departures. \*29 stations total

## CONCLUSIONS and FUTURE WORK

**This research serves as a first look** at the relationship between drought and the synoptic air mass signature of the Midwest region. Only the most intensive drought intervals are scrutinized since these episodes produce the most expensive, expansive and, at times, utterly devastating effects to the agricultural business and industries blanketed across the region. This information is particularly important to understand since: 1) the Midwest is often overlooked in the scientific assessment of U.S. drought even though many extreme droughts are documented in this region, 2) synoptic patterns are rarely incorporated into drought predictive tools, perhaps because these relationships are unknown, and 3) the results of this research indicate that there are important, variable, and complex relationships between droughts and air mass frequency in the Midwest. The methodologies used in this investigation prove quite successful in addressing the synoptic problem of drought in this region. Ultimately, this research sets out to identify the tendencies that particular air masses and groups of air masses exhibit during significant droughts of the last decade. A difference assessment is performed between “normal” conditions, as determined by a baseline frequency analysis, and an extreme drought frequency analysis. Three air masses are then further evaluated for even more input on the overlying synoptic conditions present during drought in a seasonal difference assessment. The statistical significance of the observed departures is assessed to provide additional

insight into air mass tendencies during drought.

The primary findings indicate that under normal conditions, the DM air mass is the most frequent in the region with a frequency range of approximately 25-35% during the decade. The northernmost regions such as Duluth, MN, exhibit more DP air masses than DM types which can be attributed to the great influence of dry, cold air masses from the continental interior of Canada. The second most frequent air mass for much of the region is DP except in the southernmost areas, such as St. Louis, MO, where it is MT. It appears that the influence of warm, moist air in the region's south may also be a result of proximity (here, to the Gulf of Mexico) but perhaps also indicates that average synoptic patterns display an enhanced meridional upper-air flow so that the MT frequently reaches the Midwest stations.

The DT air mass is the least frequent for all locations with a frequency range of 1-5% indicating that the hot, dry southwestern air flow does not frequently affect the region unimpeded. Interestingly, the only deviation between the decadal and period of record baseline analyses is that the decade is drier than the period of record. This is inferred from the presence of more dry variety air mass types (DM, DP and DT) over the 10-year interval. For example, the DM air mass in the decade ranges from 25-35% versus 20-30% during the period of record. This 5-10% frequency variation appears to be practically significant and should be tested for statistical significance in future analyses, though it is beyond the scope of this research to perform these analyses here.

Seasonal frequencies show substantial variation in which air mass type plays an important role throughout the year. In all seasons, the DT air mass is the least frequent type, with an approximate range of 1-10%. In spring, DM is the most frequent air mass, with ranges near 25-40%, and the MT air mass is second to DM, with an approximate range of 20-30%. The region is always under the influence of the DM air mass and the upper-air pattern most likely responsible for this is southwesterly flow that introduces dry air from the lee of the Rockies, but with large thermal modulations. The transition to summer is accompanied with a tremendous spike in the MT air mass, overtaking the DM as the most frequent. The MT frequency range is 40-45%, while the DM is reduced to approximately 20-30% at this time. This indicates that the upper air pattern may become more meridional with southerly flow introducing warm, moist air from the Gulf of Mexico into the region. The MT experiences a significant decrease during the transition to fall in which it goes from most frequent to the second least frequent, just above DT. The DM resumes its position as the primary regional air mass, with an approximate range of 30-40%, and the MT air mass ranges from 5-10%. The pattern at this time may resume to one similar to the spring. The DP air mass slightly surpasses the DM air mass as the dominant mode during the winter. The DP ranges from 30-40% and the DM ranges from 20-30%. This indicates that the flow is most likely northwesterly with cool, dry air from the Canadian Prairies, as observed in extreme

northern locations of the region throughout the year.

The overall difference assessments establish an important relationship between dry and moist air mass types during extreme drought: more dry air masses in combination with less moist air masses are associated with drought events. Of all dry types, the DT air mass displays the highest percentage of increase (approximately 0.3-5.4%) during drought events. Interestingly, this appears to be at the expense of both the DM and DP air masses, which decrease in frequency (approximately 0.1-1.3% and 0.1-2.5%, respectively) during drought. In other words, while DM and DP air masses dominate the region under normal conditions, drought episodes bring about more DT air masses. This finding is critical because it indicates that Midwest droughts, despite the season, are not only very dry but are also much warmer. Though this finding should be explored further, the thermal properties of air masses may influence drought conditions as much as the moisture content.

Similar to the DM and DP varieties, the moist air mass frequencies are also generally less during drought events. In particular, it is the MT type that displays consistent, substantial decreases of approximately 0.1-4.6%. The percent frequency change of MM and MP are small and unsubstantial during drought. This might be due to the fact that the region stays moderately moist at all times (with or without drought) because of its situation near the Great Lakes. This may also be attributed to natural variation or the fact that very infrequent air mass types in the

Midwest (*i.e.*, MP) remain infrequent during drought.

The seasonal difference assessments for three important air masses (DP, DT, MT) indicate that the extreme drought periods have some deviation from the dominant air masses during normal seasons. In spring, the MT air mass decreases by approximately 5% while the DT air mass increases by around 3%. DT air may enter the Midwest region at this time because of a zonal flow pattern situated north of the region. In summer, no change is observed in the dominant MT air mass but the DT air mass has large increases of approximately 6%. Again, more DT air masses are probably introduced during drought periods from the southwest. In fall, the most substantial decreases are observed with the DP air mass, of approximately 4%. This air mass is important during normal fall seasons and a decline is practically significant in demonstrating the regime change caused by droughts. In winter, the DP air mass decreases dramatically, indicating that thermal properties of the air masses may have a substantial impact on drought occurrence in addition to the moisture content.

These results are very important for furthering our understanding of the role of synoptic meteorological datasets and the occurrence of drought, which has never been explored in a manner such as the one carried out here. It is worth noting that the utilization of air mass frequency alone is inadequate for drought predictive purposes. The intended scope of the project was to simply uncover the relationships to possibly include these in future drought predictive tools. Aside from the obvious agricultural

interest, this research may also provide beneficial information to water managers, insurance agencies, drought forecasters and emergency management officials. For example, drought forecasters (and other atmospheric science realms) can utilize the findings of this assessment in the development of future indices and algorithms that include upper-air information. Outside of the discipline, others can incorporate this information into their own decision support systems and operating procedures.

Future research that stems from this assessment will hopefully assess the departures from seasonal normals of the remaining four air masses. For instance, the DM air mass, while not selected here, exhibited similar tendencies to DP, though to a lesser magnitude. The MM and MP air masses did not show any substantial tendencies; however, further assessment may be desired. The TR air mass was not discussed in significant detail during this evaluation, and is believed to have some unique properties regarding drought occurrence which should be explored further. Finally, the MT air mass was not sub-divided into the MT+ and MT++ air mass types that are available. Division of the MT air mass category may yield new findings beyond this discussion. In addition, DT air mass sub-divisions may provide even more information in future assessments of the relationship between synoptic and drought.

Perhaps most importantly (and a procedure already underway), it is highly advisable that future analyses assess the statistical significance of all air mass



departures from times of normal conditions. The correlation coefficients will be determined and standard deviation thresholds will be assessed. Furthermore, this research has grouped all drought days into a single albeit robust set of extreme drought days. Future works could perform an identical analysis for individual drought periods and for regions across the country.

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